Titanic, The Anatomy of a Disaster
A Report from the Marine Forensic Panel (SD-7)

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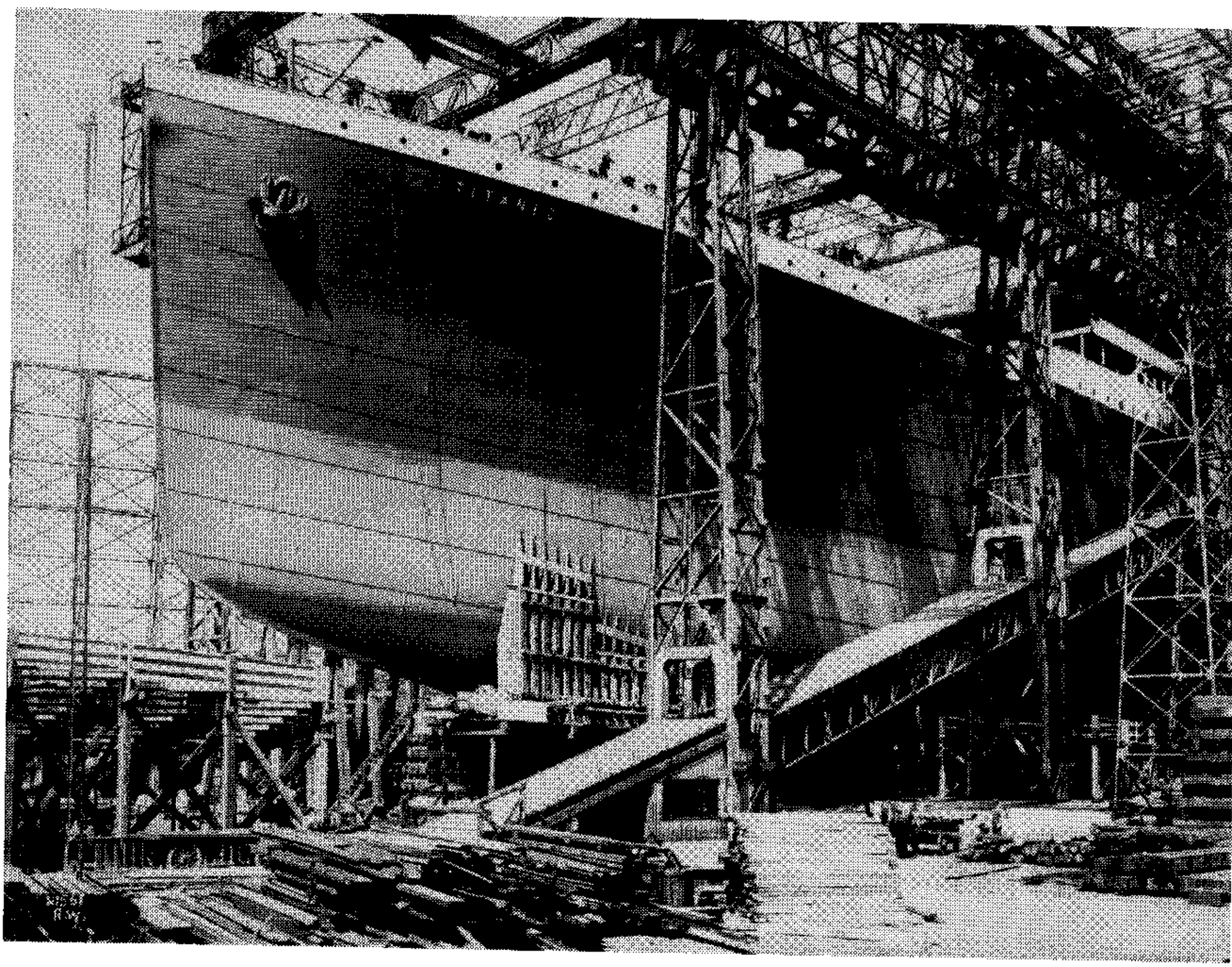
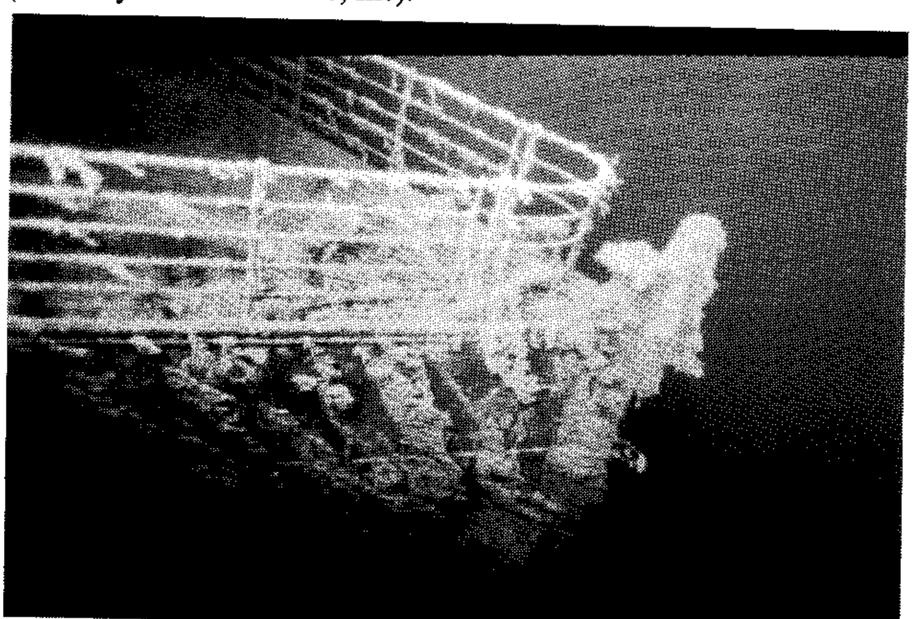


The Titanic is perched on the building ways at Harland and Wolff Shipyard on May 31, 1911 several hours before her launch. Note that the second full plate within the boot topping is the plate that sustained damage from the encounter with the iceberg on April 14, 1912. (Courtesy of the Ulster Folk & Transport Museum)

Authors Garzke and Livingstone are shown studying prints of the original drawings of the *Titanic* on board the *Ocean Voyager*in August 1996. These drawings combined with a review of survivor testimony, the sonar scan by Paul Matthias, and two visits by Livingstone to the wreck site with the submersible *Nautile* helped to formulate how this great ship broke apart and sank on the night of 14-15 April 1912 (Courtesy of RMS Titanic, Inc).



The bow of the *Titanic* is shown in her resting place in August 1996. There is quite a difference between the ship on the ways and in the advanced state of decay. About 20% of the hull has been consumed by "rusticles" which are large colonies of bacteria that are leaching out the iron and other elements in the hull. We estimate in approximately 200 years, the wreck will have collapsed and the elements will be combined with the bottom ocean sediments (Courtesy of RMS Titanic, Inc).

ABSTRACT

Many mysteries surround the loss of the Titanic. *In August 1996, a scientific investigation organized by Mr. George Tulloch of RMS Titanic, Inc. and the Discovery Channel sought to solve some of these. What was the extent of the iceberg damage; was there a missing third piece; and was the steel's metallurgy a factor in the loss? With the aid of a sonar scan, metallurgical testing, and a finite element analysis, it was confirmed that the area of damage was less than 13 square feet. It was also determined that the forces created by the flooding and the steel metallurgy brought about the hull's failure and the ship broke into three large pieces during her plunge to the bottom. A micro biology study of the wreck indicates that 20% of the wreck has been eroded away by corrosion and microbes. Some of the latter are new organisms previously unknown to biologists.*

The Marine Forensics Panel (SD-7) was created by the Society of Naval Architects and Marine Engineers in March 1995 and now is supported by five other societies[1]. To improve its expertise, the Panel has been studying such wrecks as the *Titanic*, *Lusitania*, *Edmund Fitzgerald*, *Britannic*, the British cruiser *Edinburgh*, and the German battleship *Bismarck*. After the paper on the *Titanic* and *Lusitania* was presented to the Chesapeake and New York Sections of the Society of Naval Architects and Marine Engineers in 1995 by five members of this Panel [7], it was published in the October 1996 issue of this Society's *Marine Technology*. Three of the authors, however, have continued to explore the loss of these two ships, searching for new evidence that would either confirm or dispute our findings. As the chairman of this newly formed Marine Forensics Panel (SD-7), Mr. Garzke was invited by the Discovery Channel[2] and Mr. George Tulloch of the RMS TITANIC, Inc. to participate in the *Titanic* '96 Expedition that analyzed the wreck from scientific and engineering viewpoints. There have been eight expeditions to the wreck site of this once great ocean liner, but technical questions still remained. The 1996 expedition sought to bring about a better understanding of what happened, using an unusual mix of technical, scientific, and historical expertise.

<u>The trip to the *Titanic*'s wreck site</u>. Four of the authors boarded the *Ocean Voyager* in St. Johns, Newfoundland to spend one week investigating the wreck site of the *Titanic*. Mr. Garzke was joined by Mr. David Livingstone, a senior naval architect from Harland & Wolff, builders of the *Titanic*, who brought with him some prints of the original working drawings of the ship for reference. We immediately mapped out a strategy to investigate the important points of the *Titanic* wreck from the aspects of materials engineering, naval architecture, and marine engineering. Also joining the research were Charles Haas and John Eaton, historians of the *Titanic* tragedy, Dr. Roy Cullimore, who was to study the biology of the wreck site, and Paul Matthias of Polaris Imaging, who had completed a week of sonar imaging study of the bow wreck and debris field. Before his departure, Mr. Matthias briefed Messrs. Livingstone and Garzke on some important aspects in his survey of the bow wreck. Based upon all of these discussions, the authors set some important goals in their research:

- Identify the damage caused by the collision with the iceberg.
- Investigate the entire point of rupture on the aft end of the bow wreck.
- Investigate the stern wreck and its point of rupture at its forward end.

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1 The American Society of Naval Engineers, the Royal Institution of Naval Architects, the Institute of Marine Engineers, the Salvage Committee of the Maritime Law Association, and the International Maritime Consultants, Inc.

2 This expedition was for the Discovery Channel production, "Anatomy of a Ship Disaster", Discovery Channel, April 13, 1997.

- Locate missing portions of the ship on the seabed since no site plan existed for the major portions of the wreck.

What we discovered when we reached the wreck site of the *Titanic* was that there was no site plan as in other archeological sites. A plan showing the major pieces of the wreckage is essential to assess how the ship broke apart. Paul Matthias made several dives in the *Nautile* to probe the bow for damage hidden by sediments and to find buried missing pieces of the hull. David Livingstone also made two dives to the *Titanic* wreck site in the French submersible *Nautile* reaching depths of 3,800 meters on August 13 and 15, 1996. A close up examination of the aft end of the bow wreck revealed that the lower portion of the main transverse bulkhead between Boiler Room Nos. 1 and 2 had failed completely and was missing. A visual examination from inside the *Nautile* revealed that at least two of the boilers in Boiler Room No. 2 were still in place. This was of particular interest to the authors. Edward Wilding, a naval architect and leader of the design team, had testified before the American liability hearing in 1916 that when the ship reached an angle of 35°, these boilers would be unseated from their foundations. This suggests that the ship's trim during the initial phase of her sinking process may have no greater than 35 degrees and may also suggest a similar inclination during the descent of the bow portion.

David Livingstone made a close inspection of the stern wreck and found that at least two of the four cylinders of both reciprocating engines were still in place. The remaining parts of the engines were enshrouded with plate from the side shell or decks, making it impossible to precisely assess what remains of these engines. We had not expected this based on videos from the 1991 IMAX Expedition. Mr. Livingstone surmised that shock damage was a factor in the stern wreck's condition as the stern portion impacted the seabed.

On August 15, 1996, two pieces of steel were brought to the surface, one from the side shell and another from the bulkhead between the Reciprocating Engine Room and Boiler Room No. 1.. The metallurgical analyses of this steel were to be performed at the University of Missouri-Rolla under the direction of Professor H.P. (Phil) Leighly, Jr. who was joined later by Dr. Timothy Foecke of the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland.

The Coal Fire. One of the great mysteries of the *Titanic* was the coal fire that burned in one of her bunkers throughout most of the journey from Belfast to Southampton and from there on her maiden voyage toward New York. Did this fire have any bearing on the hull failure or subsequent flooding after the iceberg impact? The firemen's testimony from the American and British inquiries was examined to determine if there was a fire and, if so, the degree of damage to the structure.

Spontaneous combustion of coal had caused a stubborn fire in the starboard bunker in the aft corner of Boiler Room No. 6. Fireman J. Dilley testified before the American inquiry held by Senator Smith of Michigan[3] that he had been among 12 men assigned to fight this coal bunker fire. The coal on top of the bunker was wet, but the bottom of the pile was dry. The coal pile began to smolder. The fire was detected from its sulfurous odor during the ship's departure from Southampton on her maiden voyage. It is uncertain how long this fire had burned, but from testimony of surviving stokers at the inquiries, it appears that it burned for at least 72 hours. The 12-man crew made every effort to put it out. Those fighting the fire were alarmed at their inability to extinguish it. The engineering officers instructed these men not to converse with the passengers so as not to alarm them.

Mr. Dilley indicated in his testimony before the Mersey Inquiry, concerning this fire, that while it was still burning, there was talk among the stokers that once the passengers were put ashore, New York City fireboats might have to be called to help extinguish it. As a precautionary measure to prevent a coal pile fire in the forward starboard bunker of Boiler Room No. 5 through heat transfer, the coal there was also fed into the furnaces. It is believed that the fire was extinguished during the evening watch (4-8 P.M.) on Saturday, April 13, by a combination of wetting down the coal pile with a fire hose and ultimately removing the burning coal into the furnaces.

During the period the fire burned, steel in the lower corner of the transverse watertight bulkhead between Boiler Room Nos. 5 and 6 ultimately became cherry red[4]. This meager metallurgical evidence, gleaned from the testimony of stokers at the inquiries, indicates that the steel temperature was near a sufficient level for the formation of

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3 Pages 96-102 of "Wreck and Sinking of the *Titanic*" by Marshall Everett, L.H. Walter, 1912, Reference [2].

4 From the testimony of Leading Fireman Charles Hendrickson at the Mersey Inquiry.

austenite. However, pouring of cold water on the area with a fire hose to extinguish the fire did not create the proper conditions for the formation of martensite, a very brittle phase of steel, that requires a rapid quenching of the heated area. A bulkhead plate retrieved from the wreck site was heated to 1500°F and then quickly quenched in 45°F water. This test at the University of Missouri indicated that the grain quality of the steel had changed very little indicating that the coal fire probably had little effect on the grain properties of the bulkhead steel.

On 9 June 1912, Mr. Thomas Lewis, the attorney for the British Seafarer's Union, questioned Edward Wilding on the coal fire before Lord Mersey. When asked about the brittleness of the steel resulting from the fire, he responded, "It would not be brittle like a piece of sheet glass, but it might be more brittle than in an undamaged condition." When Mr. Lewis questioned whether the steel would be more brittle than in an undamaged condition, he responded, "It might be a little more - yes, somewhat more."

We have also learned from the testimony of Leading Fireman Charles Hendrickson that he had observed some dents or buckles in the plate of the main transverse bulkhead between Boiler Rooms Nos. 5 and 6. These deformations were likely caused by thermal stresses in the plate, induced by the heating and cooling action of the fire. The deformation between the stiffeners could have been as much as 0.25 inch. From the testimony of those in the surviving engine crew, it appears that the plate adjacent to the inner bottom level was likely buckled slightly out of plane. It is not clear, however, whether the bulkhead's channel stiffeners were involved. There is some evidence that Thomas Andrews and some of his staff examined the bulkhead. After his inspection, it was reported that Andrews wanted the plate and stiffeners to be replaced at the *Titanic*'s first yard maintenance period after her maiden voyage.

Such a fire may also have deformed the bulkhead stiffeners, weakened the bulkhead's riveted connections, and destroyed the metal to metal and split caulking in way of its plate seam at the Inner Bottom level, thereby reducing this bulkhead's ability to remain watertight. The loss of the seal in the fire-affected area could have allowed slow seepage of water through a riveted seam when Boiler Room 6 filled with water. This leakage could have taken place around the rivets themselves in the lower course of bulkhead strakes.

Narrative of the *Titanic*. Ahead of *Titanic* on April 14, 1912 was a vast ice floe, 10 miles wide and 300 miles in length. This floe of ice was reported to be one of the heaviest of the twentieth century, with that of 1986 being the worst[5]. The French liner, *Touraine*, radioed early on the afternoon of April 12, 1912 and again at 2100 that there was substantial ice in the western Atlantic. The first warning was nearly 60 hours before the fatal collision. During the day of April 14th, the *Titanic* received seven ice warnings, one of the last being from the steamer *Mesaba* at 2130:

> "Ice report. In latitude 42 north to 41.25 north, longitude 49 west to 50.3 west. Saw much heavy pack ice and great number of large icebergs, also field ice. Weather good, clear. MXG"

While the *Mesaba*'s message was being received, radio operator Jack Phillips began receiving a number of personal radio messages as the *Titanic* came within range of Cape Race, Newfoundland. Phillips did not acknowledge receipt of this navigational message, however, and never delivered it to the bridge. Normally, radio messages pertaining to navigation took precedence over passenger radio traffic. In addition, the message was signed "MXG" instead of "MSG" which would have required Captain Smith to acknowledge its receipt. It is speculative whether history would have been changed if Captain Smith or the bridge personnel had seen this latter radio transcript. Captain Smith did, however, make at least two course alterations earlier in the day based on radio messages of ice conditions from other ships. These course changes took the *Titanic* further south of the normal ship lanes for April.

Collision. The night air and waters through which the *Titanic* passed on 14-15 April 1912 were unusually cold for that time of the year. The sky was clear with the last quarter moon rising early in the dark hours of the morning. There was no wind and the seas were unusually calm with not even a swell. In fact, the water surface, devoid of even a ripple, even reflected starlight. Such unusual ocean conditions made it difficult to detect the presence of icebergs, particularly if their darker side was positioned toward any ship lookout. Around 2330, lookouts Reginald Lee and Frederick Fleet in the crow's nest were scanning the horizon for icebergs when they detected a heavy haze ahead. Without binoculars, the two lookouts tried to determine what lay in their ship's path. Shortly before 2340, Fleet was able to observe the dark image of an iceberg, around 500 meters directly ahead, so he rang the bell three times and phoned the bridge advising the personnel of his sighting.

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5 Reference [3], pp 90-106.

Instinctively, First Officer Murdoch pulled the engine telegraph to "STOP" and then ordered Quartermaster Robert Hitchens to turn the wheel hard over to starboard[6]. The *Titanic* first veered slightly to starboard before beginning a turn some 20 degrees to port over a distance of a little more than a fifth of a mile. This maneuver, however, was not sufficient to avoid hitting the iceberg materializing on the starboard side of the ship. Murdoch then gave his final order to turn the rudder hard to port in a desperate measure to turn the ship's stern away from the iceberg and avoid a collision that could damage the blades of the outboard propeller. Following Murdoch's orders, Hitchens turned the wheel as far as it would go. Meanwhile, Murdoch sounded the alarm, warning personnel that the watertight doors were closing, and then finally pulled the lever activating the doors. Subsequent movements of the vessel indicated that the initial "STOP" order was followed by a "SLOW AHEAD", another "STOP", a "SLOW ASTERN", in 10-minute intervals and finally a "STOP" after 5 minutes. Thus by 0010, the *Titanic* was making no headway and was adrift on the ocean.

Once the order to stop was conveyed by telegraph to the engine room , the steam flow to the steam turbine was cut off. With the absence of power to the centerline shaft, the propeller wake past the single centerline rudder was substantially decreased, making the ship less maneuverable. In addition, the iceberg was very broad and its size was estimated to be approximately 180,000 to 300,000 tons (surely more than a match for the *Titanic*).

Iceberg impact. With the rudder hard over to starboard, there was a small initial transfer to starboard before the rotation generated enough forces on the hull to begin a port turn. With only 500 yards between the ship and the iceberg, there was not enough time or distance to completely avoid a collision with this ice mass.

Crew and passenger survivor testimonies differ on the severity of the impact between the ship and iceberg. From the crow's nest, Fleet and Lee noted that there was not much noise other than the sound of ice falling onto the fo'cstle and well decks. Other survivors noted the large amounts of ice scattered over these decks and in the forward ends of the open promenades. There is a photograph of an iceberg with a red smudge at its waterline, reportedly the one that the *Titanic* struck[7]. This iceberg also shows a freshly made cavity well above the iceberg's waterline and above the red paint believed to be from the *Titanic*. We now postulate that a spar from the iceberg broke off during the ship-iceberg collision, leaving that cavity. This encounter may also account for the intermittent flattening of the pipe railing on the fo'cstle deck. Inside the ship, several survivors noted a scraping or bumping noise as the iceberg slid by astern in its brush with the ship. Personnel on the bridge noted a long gradual grinding type impact during the slow turn to port as the two masses encountered each other. To those in the engine rooms below, it sounded like thunder.

Passenger Edith Russell[8] had just entered her starboard cabin (A11) on the Boat Deck, one deck below the bridge, to retire for the night. She noticed a very slight jar, then a second quick one, that seemed closer and a little stronger. The third jar came as a shock, strong enough to make her grab her bedpost. She also felt that the ship had come to a stop. Turning toward the starboard window, she observed a white shape, like a mountain, gliding by. Curious to determine what the object was, she donned her fur coat and ran onto the deck, where she learned that the ship had hit an iceberg. Looking aft, she was able to see it drifting astern and soon it was out of sight. Looking down to the Second Class deck, she observed some stokers walking across an ice-covered deck and could hear it crunch under their boots.

In Edith (nee Brown) Haisman's biography, she remembered feeling three distinct blows, verifying Edith Russell's testimony. Such testimony is important to the analysis of the bow damage because the Haisman and Russell recollections confirm the impact and momentum theory associated with the iceberg-ship encounter. It also provides a measure of the severity of the ship response. When she collided with the iceberg, the *Titanic*, being the lighter and having the greater velocity of the two bodies, rebounded. The ship's forward momentum, coupled with its increasing beam, brought it into contact with the iceberg for several encounters, each a little stronger than the first. These combined factors helped account for the intermittent

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6 At the time of the *Titanic*, the order to the helmsman to turn to starboard was "Starboard your helm!" which was actually to turn the ship to port. From the early 1920's several maritime countries changed to wheel orders (e.g. "Port your wheel!")., but the change was complete by the early 1930's. During the interim, things were very confusing to pilots who had to work with different orders on ships from different countries.

7 See Reference [4], page 141.

8 Edith Russell gave an account of her experiences aboard the *Titanic* in the May 1964 issue of the Ladies Home Journal.

scraping sounds. Inside the ship nearer to the encounter, it probably sounded more like a sledgehammer first beating on an empty steel drum and then being dragged along it. This is why, as will be seen later, the damage to the hull is isolated by compartment and not continuous from the point of encounter until the point of departure between the two bodies. It also appears that the iceberg may have had a small projecting ridge or spar that was massive and hard enough to cause riveted seams to part and the wrought iron rivets to fail. Also, the ship may have sheared off part of this ridge or spar.

Captain Smith was awakened by the noise of the impact and at once rushed to the bridge. Thomas Andrews, the managing director of the design department at Harland & Wolff, the shipyard which had built the ship, reported feeling a slight jolt. Alone in his cabin (A36), he was summoned to the bridge to speak with Captain Smith. Together, these two men would make a survey of the forward part of the ship to determine the extent of the damage. To avoid alarming the passengers, they used the crew's accesses. What Andrews and Smith would discover was that the *Titanic* was taking on water in six compartments with Cargo Holds 2 and 3 flooding at an alarming rate. There was slow water seepage in a seventh compartment, Boiler Room #4, but this flooding was still being controlled by pumps in that space. When Andrews returned to his cabin he made some quick computations and then went back to the bridge to inform Captain Smith that the *Titanic* would remain afloat for only two more hours.

The Andrews-Smith inspection of the forward compartments found that the Squash Court was half filled with water, the Mail Room was taking on water very quickly, and it was necessary for the five postal clerks there to move the mail sacks from F to E Decks. None of these men survived the disaster, because they were drowned by the fast flooding water. Andrews and Smith inspected Cargo Hold No. 2 and found water climbing up its sides rapidly. The flooding of Cargo Hold No. 2 was a rather eerie sight, because the lights in this space were still on despite being submerged.

Naval architects recognize the agony that Andrews must have felt during this inspection. He must have experienced great distress as he recognized with certainty that the pride and joy of his creation was destined to sink. However, as he accepted the fact with calm resignation, he resolutely advised Captain Smith to start an immediate evacuation of passengers.

Thomas Andrews realized that with six compart-ments flooding the ship was going to sink. He knew from flooding calculations performed during the ship's design that she would barely stay afloat with the first four compartments flooded. However, water was seeping into two others, Boiler Room No. 5 at a very slow rate and Boiler Room No. 4 in a trickle. Pumps kept the flooding in these latter two spaces under control, but he was worried about the transverse bulkhead between Boiler Room Nos. 5 and 6 that had been weakened by the coal fire. Andrews must have known from his inspection of that bulkhead on April 13th that it would be only a matter of time before it could no longer retain watertight integrity. He also knew that the non-tight coal bunker bulkhead in the starboard corner of Boiler Room No. 5 had a limited capacity to withstand a hydrostatic head. Once this happened, the ship would certainly sink. In actuality, it took about 80 minutes for this to occur.

Edward Wilding, in testimony before the British Inquiry and the 1915 American liability hearings in New York, estimated the overall damage to the ship from the iceberg collision to be 12 square feet based on estimates from survivor testimony. The collision-damage area was later estimated at 12.60 square feet, based upon a 1995-1996 computer analysis using Wilding's testimony by John Bedford and C. Hackett [5]. However small these openings were, they were sufficient to provide an inflow of water that would sink the ship. Using a mean draft of 32.25 feet, a stern trim of 3 feet and a coefficient of discharge of 0.485 at the time of her iceberg collision[9] created a significant pressure differential. The very small area of damage also fits the sinking sequence as we now know it from the sonar scan. The damage, however, was spread over seven watertight compartments, with the most severe damage occurring in Cargo Holds Nos. 2 and 3 as well as Boiler Room No. 6. During the early stages of flooding, pumps kept the water in Boiler Room No. 5 below the floor plates while the small amount of inflow into Boiler Room No. 4 was controlled by pumping. Thomas Andrews suggested to Captain Smith that every effort be made to keep intact compartments watertight to prolong the ship's stay on the surface, in the hopes that rescue ships would arrive in time to save the passengers and crew.

Ship List. During the early stages of the sinking process, the *Titanic* had a slight list to starboard. This was due to the differences in permeabilities between the

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9 This draft and trim were based upon an average of three voyages of the RMS *Olympic* and expenditure of consumables, such as coal, water, and provisions, to the point when *Titanic* sank from Reference [5].

starboard and port coal bunkers and the Firemen's Passage in Cargo Holds Nos. 2 and 3. The Firemen's passage can be likened to a watertight tunnel some 10.5 feet high above the tank top level. The nature of its construction confined the early flooding in these two holds to the starboard side. However, once the flooding waters reached a depth of greater than 10.5 feet, the port side of these two holds began to flood, gradually reducing the starboard list. The Firemen's Passage also flooded from damage it sustained from the collision.

During the final stages of flooding, when the ship sank deeper into the water, the stability curves, produced by Hackett and Bedford [5] indicate that the ship had much greater sensitivity to list from shifting weights such as passengers moving from one side to the other. By the time the *Titanic* actually sank, there were over 1,500 people still on board that equated to a potential shifting weight of some 110 tons and a potential moment change of some 9,000 foot-tons if all of these people went from one side to the other. Wilding estimated that 800 people moving through 50 feet would cause a 2-degree list which is equivalent to a 1 in 28 slope of the deck. The transverse stability of the ship remained rather substantial until 10 minutes before the ship broke apart. Any list prior to this time was due to unsymmetrical flooding.

Passenger Evacuation. It was not until 0025 on 15 April that passengers began to board the lifeboats. Although the *Titanic* was equipped with considerably more lifeboats than the legal requirement, those aboard would only accommodate about half the number of people on the ship (even though their capacity was considerably more than the Board of Trade's requirement for a vessel of 10,000 or more gross tons). This was due to the mistaken assumption that a ship the size of *Titanic* would take hours to sink and that the lifeboats would serve as a means of transferring passengers to other ships in emergencies. By 0120, only six lifeboats had been launched. During an October 1993 interview on the *Titanic* for the Discovery Channel, Eva Hart noted that in the first hour of evacuation, the footsteps she heard on deck were casual; those during the last hour were more frenzied as people, realizing danger, began to access the lifeboats once the bow sank below the surface. Also, there was a lull until the water reached sufficient levels to begin flooding compartments such as Boiler Room No. 4. People did not feel that the ship would sink and were hesitant to access lifeboats. Therefore, based on the apparent confidence of the passengers and crew concerning the invincibility of the *Titanic*, we believe that even if more lifeboats had been provided, there still would have been a significant loss of life.

Sonar Imaging of the Bow Wreck. During the week of July 29-August 3, 1996, Paul Matthias of Polaris Imaging used a sub bottom profiler to survey the bow portion of the wreck below the sediments, to determine the damage from the iceberg. He also used his 50 kHz side scan sonar to survey the debris field and determine if there were any hidden pieces of the ship in the sediments.

The sub-bottom profiler was mounted on the arm of the *Nautile* and was used to image the hull buried beneath the mudline. It was oriented at an oblique angle so that the energy was focused diagonally downward from the submersible to the side of the hull. While the metal hull caused a strong energy return, the openings or separations showed up as distinct dark lines. By employing the position and attitude of the submersible and the location of the hull combined with an estimated velocity of the sound from the consolidated sediments around the hull, Mr. Matthias was able to estimate the locations of the separations. While the profiler was able to discern an edge for an opening, it was not able to determine the width of the openings in the *Titanic* because they were narrower than the profiler's resolution.

The side scan sonar was mounted on the stern of the submersible. This equipment was the only commercially available sonar able to withstand pressure at 12,000 feet of water. The low frequency of 50 kHz provides a low resolution while detecting relatively small objects, but can resolve large shapes as well. The sonar transmitted

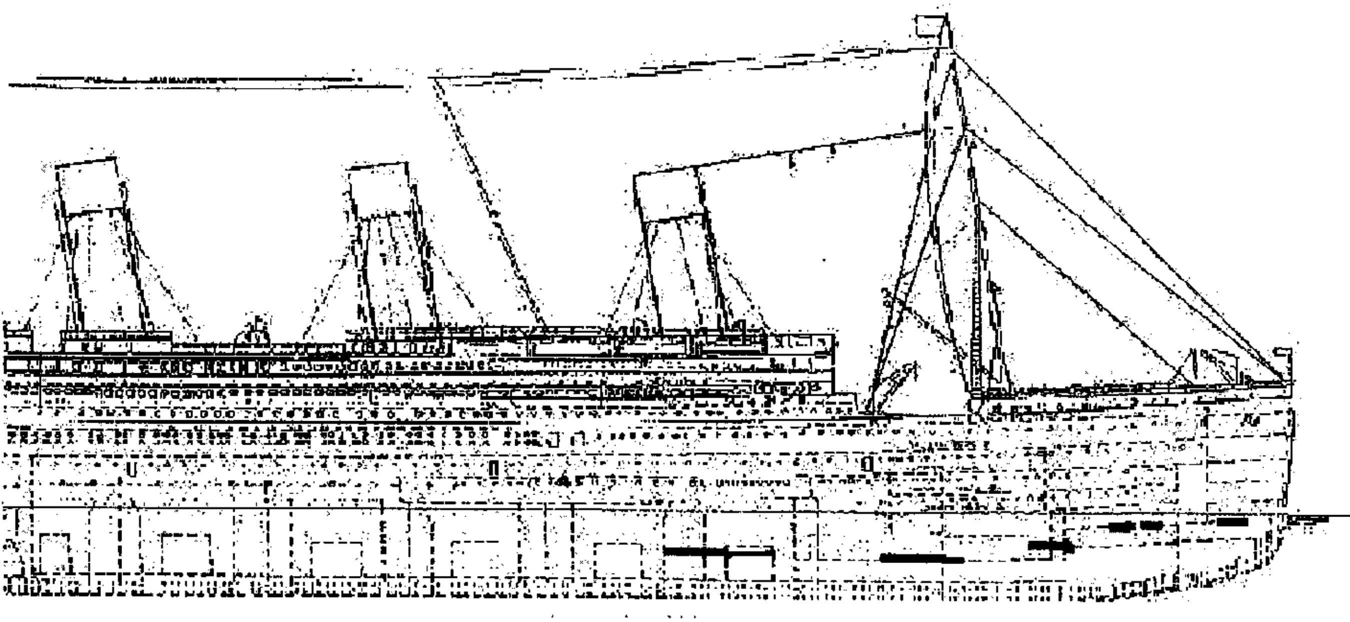

Image Courtesy of Polaris Imaging, Inc.

Figure 1 <u>Illustration of the Iceberg Damage</u>

The top portion of the riveted seam of the first full plate below the boot topping was opened in the forepeak and cargo hold number 1. As the ship-iceberg envounter continued, there was fracturing and tearing of this plate between cargo holds Nos. 1 and 2, and parting of the lower portion of that plates riveted seam between Cargo Holds Nos. 2 and 3 and Boiler Rooms Nos. 5 and 6.

narrow pulses to port and starboard 7.5 times per second to image a total swath of 200 meters. The objective of using the sonar was to complete the first archeological map of the seabed between the bow and stern sections of the ship, as well as aft of the stern section. This map indicated a much higher concentration of artifacts near the stern section in the field between the bow and stern. It also detected a high concentration of debris near the broken opening of the stern section. This pattern may be related to the more vertical path of the stern section and its greater impact with the seabed than the bow section. The debris pattern near the broken opening of the stern section trails away from the port side, indicating the likelihood that this corner impacted the seabed first.

The sonar and seismic measurements, as well as the navigated position data, were collected with EOSCAN, a digital-imaging acquisition, processing and display system. EOSCAN allowed the a real-time processing of the collected data within the submersible. The simultaneous collection of the sonar and profiler measurements was essential to positioning the hull separations with the profiler, and the objects within the debris field using sonar.

The sonar images were collected with the sub at a height of 10 meters above the bottom. For verification and validation, inspections were frequently done on objects indicated by EOSCAN.

Most of the damage to the bow section is hidden by sediments up to the anchor level on the starboard side and to a lesser extent on the portside. In fact, there is a small trough between the hull and sediment on the port side. This is believed to have formed over the years from the bottom currents flowing by the port bow.

The 300-foot Gash. Prior to 1985 many authors depicted the damage caused by the iceberg to be a 300-foot gash as a result of the testimony given at the British Inquiry. With the discovery of the *Titanic* wreck in 1985, no evidence could be found of such damage on the exposed portion of the bow wreck. In papers by Garzke et al in 1993 [6] and again in 1995 [7], this gash was disputed and believed to be sporadic-type damage. This conclusion was supported in papers published by John Bedford and C. Hackett in 1995 and 1996 (Reference [5]), who also found this damage to be intermittent. Their conclusions were based on computer studies using naval architect Edward Wilding's computations and sketches attempting to recreate the flooding that the *Titanic* might have experienced based on survivor testimony. Bedford and Hackett [5] determined that the damage, in fact, was no more than 12.6 square feet; this substantiated findings done by Edward Wilding that the damage area was no more than 12 square feet. Many people could not accept that such a small area of damage could sink a ship as large as *Titanic*.

Paul Matthias' survey of the starboard bow helped to reveal what may have happened to the ship in her encounter with the iceberg. It must be remembered that the damage seen from the sub-bottom profiler through 16.75 meters of sediment may have been exacerbated by the bow's encounter with the seabed. When the bow swept down at a possible speed of 30-45 knots, it moved across the seabed at an angle, plowing up sediments in its area of encounter as it slowed down. This action forced a slurry of sediments through the openings made by the iceberg and filled spaces like Cargo Holds Nos. 1, 2, and 3. The presence of sediment within the *Titanic* was observed during passes of *Nautile* over these spaces during the 1996 Expedition.

Iceberg Damage. How did the *Titanic* encounter the iceberg, and what damage did she sustained? From the results of the sub-bottom profiler survey, we believe that six openings were made in the *Titanic*'s hull in her impact with the iceberg[10], all within a time span of about 11 seconds (see Figure 1). The first brush with the iceberg was a minor glancing blow in the forepeak area just below the waterline near the top of a rivet seam, at a speed of approximately 20 knots. A trace of damage to the side shell was observed at a riveted seam in the sub-bottom profiler of the forepeak, just below the waterline. Because of the narrow bow sections and since the ship was maneuvering to port, this area of the *Titanic* had more of a brushing encounter with the iceberg. However, as the ship continued her forward advance, this brought her back into contact in separate areas of Cargo Hold No. 1 at a speed of less than 20 knots. The profiler discerned two separate areas of damage of 1.2 and 1.5 meters in length along what is believed to be a riveted seam, again just below the waterline. These two encounters were sufficient, however, to shear away a portion of the underwater portion of the iceberg. During these clashes with the ice mass, she was continually slowing from her

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10 The imaging provided the horizontal extent of the six openings. The width of these openings was below the resolving power of the sub-bottom profiler.

initial speed of 21.5 knots.

As the ship continued to lose speed in her brushes against the iceberg, a fourth opening was made by the iceberg between Cargo Holds Nos. 1 and 2. During this rendezvous, the damage to the ship was further below the waterline as it appears that an upper ledge of ice had been sheared away causing contact further down below the waterline. The sub-bottom profiler shows damage approximately 4.6 meters long at midspan of a plate and in way of a main transverse bulkhead. There was damage about one meter inboard along this bulkhead. It is our contention that the impact forces during this iceberg encounter were sufficient to fracture and tear the plate and transmit structural damage from the main transverse bulkhead between Cargo Hold Nos. 1 and 2 to an inner longitudinal bulkhead that formed the outer boundary of the starboard access to the Firemen's Passage. The structural damage also involved the wrought iron rivets. Stoker Charles Hendrickson noted in his testimony that water was coming through this bulkhead near the bottom of this access. Sonar imaging does show damage along the shell and across the main transverse bulkhead at this level. Although Edward Wilding testified that he thought it to be a penetration by the iceberg that caused this flooding, we do not believe that the iceberg penetrated the ship's plating. First, ice is softer than steel and second, the wrought iron rivets were more likely to fail, opening a seam to flooding.

After the encounter around Cargo Holds Nos. 1 and 2, the ship moved slightly away, but her slower speed and increasing width of hull brought her back in contact for a far more serious blow even further below the water surface. Such contacts were serious because the steel plates and rivets were very susceptible to impact failures. The plate samples retrieved from the seabed had missing rivets and some missing their heads. In addition, one plate had steel pulled out from the rivet hole to the edge of the plate. The sonar imaging shows a large area of damage about 10 meters in length between Cargo Holds Nos. 2 and 3 at a riveted seam. The more severe failure appears to be in Cargo Hold No. 3, substantiating the work of Bedford and Hackett [5] that the damage was most serious in this space. Edward Wilding had also thought that Cargo Hold No. 3 absorbed the brunt of the impact. The damage seen in the sonar imaging also explains why this particular space filled so quickly with water, more so in the first hour than any of the other six compartments affected. By this time, the ship's forward speed had been significantly reduced. Nevertheless, the ship rebounded slightly, and came back again in contact outside Boiler Room No. 6 at the same riveted seam for its sixth and last encounter. These last two encounters were at a distance of 20 feet below the waterline. By this time, the ship's forward speed had been considerably reduced.

In the encounter outside Boiler Rooms Nos. 5 and 6, the energy of impact was less as the ship had begun to turn away from the iceberg. However, it was sufficient to cause a shower of ice to fall from an above-water spar of the iceberg onto the ship. The sonar imaging shows a 13.7-meter length of scraping-type damage of which the most severe damage was the parting of a riveted seam in Boiler Room No. 6 and the forward corner of Boiler Room No. 5. There is also a large dent in the hull in the forward end of Boiler Room No. 5, near the main transverse watertight bulkhead between these two spaces. At this point, as the ship began to turn away from the iceberg, there was a compressive pivoting action against the ice, causing this dent in the shell plating in the area of the main transverse bulkhead between Boiler Rooms Nos. 5 and 6.

All the damage in the six areas cited in the foregoing paragraphs is in isolated areas extending from the bow to a point just forward of the foremast. Each instance of damage may have been along a riveted seam. In Cargo Hold No. 3, the sonar imaging shows more tearing damage than plates fracturing due to brittle fracture and sensitivity to sudden blows in icy waters. The profiler was able to detect such openings since it could "see' the edges of the holes. An inspection of the shell plating plan of the *Titanic* (Harland & Wolff Hull Number 401) shows that there is a main riveted seam in the area where Leading Fireman Frederick Barrett's testimony mentioned a tear in the shell plating before the two inquiries into the disaster. We will discuss this point in greater detail.

There is a possibility that the outer strakes and riveted connections to the shell of the main transverse bulkhead between Boiler Rooms Nos. 5 and 6 were also damaged, based upon the large indentation in the side shell. It should be noted that the bow's impact with the ocean bottom could have further damaged this bulkhead, making it difficult to precisely determine how much damage was done by the collision with the iceberg. However, it does appear that the sonar scan of the damage to the shell plating outside these two boiler rooms has verified much of Stoker Frederick Barrett's testimony before the American and Mersey inquiries. (A time line of this individual's testimony is summarized in Appendix

A.) Barrett maintained that there was damage to the side shell "some two feet above the floor plate" and that water came in from what he thought was a tear in the shell. The tear that he described was near a riveted seam that was parted by the collision with the iceberg and resulted from popped wrought iron rivets and tears in the plate. The rivets are wrought iron that is a composite of ferrite, a low carbon fairly ductile phase, and a slag constituent of iron silicate, an inorganic compound that occurs in long stringers parallel with the direction of hot working. The iron silicate is glassy and quite brittle.

When the iceberg and the *Titanic* had their last encounter, the ship was beginning to turn away from her deadly rendezvous. However, the hull outside Boiler Room No. 4 had a brief brush with the iceberg that was serious enough to cause a few wrought iron rivets to fail because of their brittleness in the near freezing water. This allowed water to trickle into Boiler Room No. 4. Flooding of this space, described by stoker Dillon, was never critical in the first hour of the ship's sinking process as a 150-ton pump kept the water level below the floor plates.

The damage to the shell plating outside of Cargo Hold No. 3 was the most severe in the encounter with the iceberg and is the reason why this particular watertight compartment flooded so rapidly. The damage in this area of the ship also fits Edith Russell's and Edith Haisman's accounts of the severity of the third encounter with the iceberg as a very strong jolt. In all probability, because of the damage it received, this compartment filled faster than the other spaces involved in the collision. Flooding water from Cargo Hold No. 3 probably overflowed into those compartments forward of this cargo hold before they were filled by their own flooding action. Another important aspect of the flooding was that a number of portholes were left open by the crew and passengers for fresh air or by the curious to determine what the ship had hit. These openings were additional sources of water intake during a later phase of the ship's sinking process.

Condition of the Transverse Bulkhead Between Boiler Room Nos. 5 and 6. The damage to the bulkhead by the coal fire may have allowed some water to seep though the riveted joint between the inner bottom plating and the transverse bulkhead plating. However, there was a small amount of water seepage through this same bulkhead from the collision damage to riveted connections and damaged outer strakes. Much of this water was contained by a non-tight coal bunker bulkhead on the aft side of the main transverse bulkhead for the first hour after the collision.

No one has been able to actually observe any damage to the hull from the iceberg. During his first dive on the wreck on August 13, 1996 in the submersible *Nautile*, David Livingstone planned to locate possible damage on the starboard exposed hull near Boiler Rooms Nos 5 and 6 based on testimony of fireman Frederick Barrett. The hull is exposed from sediments here. Livingstone was to be assisted by Bill Garzke who referenced the shell plating plan of the *Titanic* on the *Nadir*. Unfortunately, David Livingstone was unable, because of time constraints, to closely examine the exposed starboard hull in the vicinity of Boiler Room No. 6. The sub-bottom profiler, however, was able to scan the area of the hull damaged by the iceberg and provides a clue as to what may have happened in the ship-ice collision.

Using the working plans, the results of the sub-bottom profiler, and the survivor testimonies of stokers Dillon, George Beauchamp, Charles Hendrickson, and Frederick Barrett from the 1912 Mersey Hearings for the Board of Trade, we have determined more precisely where the iceberg made its impact against the ship. It appears from this research that a massive and hard underwater portion of the iceberg struck the ship intermittently at a level of 4.1 to 4.7 meters above the keel. The impact was an impulse and momentum interaction whose intensity was governed by hydrodynamic forces and the changing underwater breadth of the ship at the time of the 11-13 second encounter. This might have been a bank effect as the ship closed the iceberg where the iceberg pushed the ship away, while at the same time the ship was pulled towards it.

Once a ship encounters something as massive as this iceberg, all the dynamics of turning are changed because a new effective "pivot point" is created at the point of contact. The *Titanic* may have tried to rotate around this new pivot point or, considering her mass and speed, bounce off a small distance. Once clear, the combined effects of Bernoulli (the Venturi effect when two ships come close alongside and the turning effects of rudders) and turning dynamics caused her to hit again and the cycle repeated itself - rather like a ship undergoing a hard berthing. The evidence of this is in the sub-profiler scan of the starboard side of the hull.

Discussions with Ian W. Dand of BMT SeaTech Limited produced an example of a small coastal tanker that had become trapped alongside another as they came in contact while leaving the port of Rotterdam. Due to the shape of the small vessel, as it tried to move its bow away, the point of contact with the other vessel on its quarter aft should have prevented its rudder from moving the bow very far. At certain positions along the larger ship, once the bow moved out, it was "sucked" back alongside, thereby beginning a cycle from which it was difficult to recover. By dropping back to a different point of contact, however, breakaway was possible. This was also evident during the collision of the HMS *Hawke* and *Olympic* in the Solent on September 20, 1911.

The *Titanic*'s collision with the iceberg, however, was strong enough and the ice massive enough to part a plate seam deep under water, cause the failure of some rivets and break the caulking in one of the main plating seams deep below the waterline. The sensitivity of the fracture resistance of the steel and the rivets to strain rate and low temperatures could lead to some cracking in the steel plates and rivet failures. In his testimony, Barrett testified that the collision was like thunder, but it may have also sounded like a sledgehammer hitting and scraping against an enclosed steel drum. A time line of Barrett's odyssey from 1140-1300 is attached to this report as Appendix A.

Rivets. In the ideal rivet, the axial tensile stress should be slightly less than the yield strength. When driven, a hot rivet is forced to fill the rivet hole and the heads are to fit tightly to the plates it is holding together. As the rivet cooled, it shrank, pulling the plates together. The stress created in the rivet by cooling may have exceeded the yield strength of the rivet at a particular temperature, hence some yielding would occur in the rivet. As the cooling continued, the rivet shrank, creating an axial tensile stress that drew the plates together. If the yielding strength of the rivet is exceeded, there is further yielding of the rivet. At ambient temperatures, the tensile stress in the rivet should be slightly less than the yield strength. The procedure at the time of the *Titanic*'s construction in testing whether a rivet was sound or not was to strike it with a hammer. If there was a ringing sound, the rivet was well driven. If the sound was dead, then the rivet had to be drilled out and another driven again.

Research and tests with the *Titanic steel* plates and shapes has uncovered that the rivet holes were cold punched. This practice created micro-cracks around the periphery of the rivet holes of the plates that were examined. The existence of these micro-cracks was verified in an examination of a rivet slug and hull plate from the *Titanic* that was done at the Canadian Defense Laboratory in Halifax, Nova Scotia. The slug was under a great deal of constraint during the punching operation. This constraint and compressive stress would impede the formation of cracks in the slug more than in the less-constrained plate. In addition, the clamping stresses for the rivets are axial, clamping the plates together. The cracks are radial, going out from the hole into the plate. They only stresses that are important from the rivet on stopping these cracks would be the frictional stress on the head of the rivet on the plate's surface. If the shaft of the rivet swells as the rivet is driven, it will begin to push on the interior walls of the rivet holes, providing additional loads on these radial cracks.

Chemical tests were also done on the slug to verify its element composition. Scrapings of steel around rivet holes from a hull piece retrieved from the wreck site in the 1991 IMAX Expedition were also examined. Such cracks around rivet holes were possible sources of fractures in the plates during any severe impact or stress field. However, the fractures in the collision with the iceberg would have been very localized to impact areas between ship and ice. The hydraulic riveting process added to the cracking problem by creating residual compressive stresses in the steel plate that were not relieved. The presence of micro-cracks around the rivet holes offers a possible explanation of why the rivet holes themselves were no impediment to crack propagation.

Edward Wilding was aware of the dangers in the cold punching of rivet holes. Perhaps his perception had been prompted by the collision between the cruiser, HMS *Hawke* and *Titanic*'s sister, the RMS *Olympic* in the Solent in September 1911. He noted that the steel was satisfactory according to Lloyd's Rules of that period, but he felt that an "impact" or "notched bar" test should be introduced as part of hull surveying requirements. Furthermore, he was concerned that the punching of rivet holes in plates was causing cracks to appear in the plates. (Lloyd's made a change in its rules subsequently.) Wilding, who was a former naval constructor, noted in his response at the inquiries that the reaming of rivet holes after their punching or drilling was a desirable precaution, but would add to the cost of construction. The practice of reaming the rivet holes was used in the construction of the *Lusitania* and *Mauretania* that were built to Admiralty specifications.

The parted plates, failed rivets, micro-cracks, and broken caulking allowed water to flow in. The amount of water streaming in was dependent on the severity of the encounter with the iceberg, the size of the opening in the parted plates, and, in particular, the water pressure head

This is a view of the collision damage to the RMS *Olympic* in her collision with the cruiser HMS *Hawke* on September 20, 1911 in the Solent, south of the port of Southampton. The waters in the Solent at that timne of year were much warmer than the area in which her sister collided with ice some seven months later. Note the fracturing around the rivets in the upper portion of the hole in way of the rivets. (Courtesy of Charles Haas and John Eaton,"*Titanic*, Triumph and Tragedy") resulting from the draft of the ship as she sank. For example, David Livingstone and Bill Garzke have estimated the air escaping from the air escape pipe in the fore peak tank to be around 85 mph, enough to sound like a whistling noise. The impact and momentum encounter between the ship and the iceberg punched holes in the plates in the area of contact as well as forming small fissures that might have radiated from rivet holes due to the microstructure of the steel and the cold temperature. The sea water temperature was between -1 to -2 °C, unusually cold for April, while that of the air was -1 °C on 14-15 April 1912. (The water temperature was confirmed from the log of the SS *Californian.*) We also know from testimony of Fourth Officer Joseph Boxhall that there was concern about the freezing of water in the fresh water tanks some four hours before the collision took place.

The extent to which the coal fire damaged the main transverse bulkhead between Boiler Rooms Nos. 5 and 6 contributed to the early flooding in the *Titanic* is speculative, due to the lack of confirming metallurgical evidence. However, the impact of the iceberg outside of Boiler Room No. 5 probably caused a parting in the plate at the bulkhead intersection with the shell plating around the grating level. If the fire had reached that far outboard, there is also the possibility of failures in the outboard plating of the bulkhead where the bulkhead plate had contact with the burning coal. The angle bar connections between this transverse bulkhead and the shell would have sustained some damage due to the dent in the side shell.

When Stoker Frederick Barrett first entered Boiler Room No. 5, he looked into the forward coal bunker on the starboard side, then emptied of its coal contents because of the fire. His testimony at both the American and British inquiries was remarkably consistent in describing the tear he saw in Boiler Rooms Nos. 5 and 6. He stated that the tear was a few feet into Boiler Room No. 5 and that the flow of water into this space just aft of the intersection of the main transverse bulkhead with the side shell was like that from a fire hose. Whether the outboard strakes of the main transverse bulkhead between Boiler Rooms Nos. 5 and 6 were also damaged by an inward thrust of the side shell during the iceberg encounter is not clear from the testimony of those who were in the space and survived. Coal bunker bulkheads hid the crucial outboard corner of the transverse bulkhead from direct viewing. In any event, the flooding of Boiler Room No. 5 was contained with the 150-ton per hour pump available in that boiler room. Barrett also testified that a crew of some 20-30 men was brought down to Boiler Room No. 5 to extinguish the fires in the furnaces by pouring water into them. This created steam, limiting visibility in this space. As a result, Engineer Shephard fell into an open manhole that he could not see and broke his leg. Barrett and Engineer Herbert Harvey tended to Shephard for some 15 minutes to make him comfortable and give him first aid. However, after almost an hour of intense water pressure, the non-tight coal bunker bulkhead within Boiler Room No. 5 collapsed and allowed an inrush of water into this space. Up to that point, Leading Fireman Barrett and Engineer Harvey, who had been on duty manning the pump with Engineer Jonathan Shephard, managed to escape. Harvey made an unsuccessful attempt to rescue Shephard who was swept into the portside of the space by the inrushing waters. Harvey, who saved himself, was unable to find Shephard who perished in the flooding of Boiler Room No. 5. Upon learning of the collapse of this bulkhead, Chief Engineer Joseph Bell was overheard by one of the surviving firemen to have said, "My God, we are lost".

Sinking of the *Titanic*. During the first hour there was moderate flooding in the first five watertight compartments, which caused the *Titanic* to begin trimming by the bow. There was slower flooding in Boiler Room No. 5 and a trace of flooding in Boiler Room No. 4, but the 150-ton bilge pumps in these spaces were able to contain this flooding for the first 80 minutes of the sinking process. Around 0055 the flooding boundary between Boiler Rooms Nos. 5 and 6 failed.

Flooding of Boiler Room No. 6, 15 minutes after the iceberg collision, had extinguished the fires in the five double-ended boilers there. The water level in this space was about 14 feet above the tank top at that time. Fires in Boiler Rooms Nos. 4-5 were ultimately extinguished and the pressures in all the boilers were gradually lowered by allowing steam to escape through pipes up the three stacks (the fourth being a dummy). Enough steam was generated by the Boiler Room Nos. 2 and 3 for all the dynamos to provide the necessary electrical power for the hotel services and auxiliary machinery. The sound of escaping steam from the first three stacks was noted by many who survived this tragedy. Second Officer Lightoller said "it sounded like the noise of one thousand steam locomotives".

Just before 0200, Boiler Room No. 4 began to flood through deck openings (escape ladders, vents, or electric cable passages) where the water level now reached. The flooding of this space caused the bow to sink below the water surface. Chief Engineer Joseph Bell, in a last-minute, desperate measure to control the flooding of Boiler Room

No. 4, had the watertight doors raised to Boiler Room No. 3 to allow hoses to be rigged to 150- and 250-ton pumps in that space. Boiler Room No. 4 had a single 150-ton pump. This effort had only a temporary effect of controlling the flooding, as water found its way into spaces above and began to spill down into this boiler room. At this time the fo'cstle was awash and the propeller blades were above the water surface. It was around this time that the sinking process slowed. At 0150, the pace began to quicken again as the efforts to control the flooding in Boiler Room No. 4 failed. By 0215 all the firemen and stokers were sent topside, but the engineers stayed by the pumps and later went down with the ship.

Events Around the Forward Expansion Joint. When the bow went under and the stern began to rise from the water, we have estimated the free-field stress in the region of the first expansion joint between the first and second stack reached a minimum value of 20,000 pounds per square inch. The free-field stress was higher between the root of the joint and B Deck where there was a large doubler plate. When Boiler Room No. 4 flooded, the stress levels around the forward expansion joint were sufficient to double or triple the free-field stresses, increasing the likelihood of buckling or cracking in the shell plating directly below the joint.

The high stress levels also reflected the magnitude of forces causing this expansion joint to expand and ripping off the expansion joint's leather covering on one side. The joint was performing exactly as intended to relieve stresses in the superstructure. In doing so, however, it could have caused some damage to adjacent shell structure from the large bending stress continually building from the flooding in the forward part of the ship. The aft stays for Stack Number 1 were in extreme tension when the joint began to expand. They finally snapped around 0205. This failure allowed the forward stack to fall to the starboard side and forward. As it crashed down in a shower of sparks, it damaged the Captain's Sea Cabin and the starboard bridge structure as well as killing a number of people in its path, both on the ship and swimming in the water. Second Officer Lightoller was in a position on the Boat Deck during the launching attempt of one of the collapsible lifeboats to observe the opening of the forward expansion joint and the failure of these stack stays and the joint's leather covering. He narrowly missed being struck by the falling stack structure. It is interesting to note that the *Britannic*'s expansion joints were relocated to avoid the apparent design flaw of supporting stack stays across expansion joints.

Review of the dive photography taken at the wreck site has helped to substantiate what can be seen in the finite element analysis. There are buckled plates below the joint on both sides of the bow wreck. However, on the port side there is a large bend in the side shell, averaging 3 meters in width. This bend grows in size as it disappears below the sediments. It is believed that this bend originated in those moments when the forward expansion joint was pulled apart. It was further enlarged when the bow section hit the seabed with a great force -- hence the large bend, some 3 meters wide at the point of the sediment line on the port side plate below the bridge area. However, as the flooding progressed into Boiler Rooms Nos. 5 and 4, the bending stress in way of the second expansion joint went beyond yield and the next stage of the *Titanic* saga began.

The Breakup of the *Titanic*. With a rumbling, crashing noise, the bow sank deeper into the water and the stern rose into the air. Storekeepers Frank Prentice, M. Kiernan, and Cyril Ricks felt the vibrations and rumbles in the ship as the stern lifted higher out of the water. The stern section remained motionless and high out of the water for a period of anywhere from 30 seconds to several minutes. Then it slowly began to fall back towards the water surface, only to rise again before the ship began her final plunge. Once this began the *Titanic* picked up speed as she sank below the water surface. Some of the survivors stated that the stern went to an almost perpendicular position as it slid below the water surface.

The failure of the main hull girder of the *Titanic* was the final phase of her sinking process. This began between 0200-0215 and started somewhere between stacks numbers 2 and 4. The finite element analysis indicates that the plate failures might have started around the second expansion joint or just aft of it. Stresses in the hull were increasing as the bow flooding continued and the stern rose from the water. Detailed examination of survivor testimony and underwater surveys have confirmed that the forward expansion joint was opened up. This situation while the ship was still on the surface is certainly an indication of the significant stresses induced by the flooding of the forward part of the hull. A review of the stresses from the finite element analysis in this area confirm that the stresses are well above the material yield stress.

It is believed that the second expansion joint also experienced significant stress development between the its root and the deck structure below it. As the flooding progressed aft, the hull girder bending moment increased beyond its design limitations and the stresses around this expansion joint soon exceeded the yield strength of the steel. It is thought that, ultimately, a structural failure in the hull or deck plates occurred in the area around the second expansion joint. We believe that once localized fracturing occurred in way of this joint, additional plate failures and fracturing radiated out from this joint - port and starboard. It is likely that the decks, however, with their finer grain structure[11] [8] were able to deform well into the plastic range of the material before failing in ductile tears. It is speculated, however, that the side shell plates fractured due to their coarser grain structure and inclusions. Evidence of this type of failure appears on the wreck today. Free field stresses, already at the yield point of the material, may have been increased by a factor of two to four times that in areas of structural discontinuities, such as large opening, small radii, and in way of doubler-plate edges. Fractures typically propagate in random chaotic paths likely following weaknesses in the plate and micro-cracks already present around rivet holes that had resulted from the cold punching of the thick plates. Also, crack propagation may have been aided by the low air and water temperatures which reduced the impact strength of the steel during rapid loading. It is believed that some of the fractures followed through rivet holes and porthole installations, while some even passed through doubler plates. Evidence of the latter was observed on "Big Piece" (a 4 by 7 meter chunk of plate from around C Deck on the starboard side), to be raised from the seabed in late August 1996. That effort failed.

If we assume that the hull girder failed at the surface, then as Boiler Room No. 4 filled with water, the stern rose further out of the water, resulting in some 76 meters of unsupported hull, sharply increasing the hull girder stresses and accelerating the fracturing of plates. This situation could be likened to a ship in dry dock with its stern lacking the necessary shoring. The angle of trim grew to a maximum of 15-20 degrees, further increasing stresses in the hull and deck plating near the aft expansion joint. The stresses continued to build in this area of the ship, where there were large openings for a main access, the machinery casing for the Reciprocating Engine Room, the uptakes and intakes for the boilers, the ash pit door on the port side of Boiler Room No. 1, and the turbine engine casing. As the hull girder continued to fail, the bow was first to begin its plunge toward the seabed.

As the bow and stern sections continued to separate, there were some local buckling failures in the inner bottom and bottom structure. As many eyewitnesses testified, this caused the stern section to settle back toward the water's surface as the decks began to fail and the side shell fractured into many small plate sections. The finite element analysis has indicated that the stresses in the region of Boiler Room No. 1 and the Reciprocating Engine Room were elevated.

An additional stress analysis by Arthur Sandiford (Table 1), based on classical beam theory, indicated that the hull girder stresses exceeded the yield point of the steel. The commencement of the bow and stern separation was followed by the collapse of the two main transverse bulkheads bounding Boiler Room No. 1, as they were compressed by the downward movement of the deck structures. The decks, in turn, failed due to the lack of bulkhead support. Around 0215, the lights were extinguished as the critical runs of power cabling snapped during the deck structure failures. Steam piping supplying steam to the main and auxiliary dynamos probably failed concurrently.

When the two bulkheads bounding Boiler Room No. 1 failed, the unsupported length of inner bottom suddenly grew to 165 feet, encompassing Boiler Rooms Nos. 1 and 2 as well as the Reciprocating Engine Room. This condition allowed deformation of the inner bottom structure to extend up further into the ship's machinery spaces, while the deck structure failures continued. It is believed that this compression of the hull girder brought about the failure of the side shell plates and also allowed equipment inside the ship, such as the boilers in Boiler Room No. 1 to be freed from their foundations and begin their plunge to the seabed below - just before the ship would began its final descent. As water poured into Boiler Room No. 1, hot surfaces were suddenly chilled by the near-freezing sea water which may have caused the rupture of the hot steam piping in this space. The main steam pipe to the dynamos passed through this space.

Between 0210-0220, the stern began to settle back toward the water surface. Eva Hart remarked about this

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11 CANMET's analysis of the *Titanic* steel indicates that the deck plate sample had a finer grain structure than the hull plate section.

Table 1

Summary of Bending Moment, Shear, and Stresses

Condition	Bending Moment (Foot-Tons)	Bending Moment (Tonne-Meter)	Stress (T.S.I.)	Stress (MPa)	Shear (Tons)	Shear (Tonne)
C-6	4,420,000	1,369,225	26.8	414	9,500	9,655
Intermediate	4,547,000	1,408,567	27.6	426	9,500	9,655
C-7	5,200,000	1,610853	31.5	487	9,500	9,655

Table 2

Chemical Composition of the RMS *Titanic* Steel

Element	1991 Percent	1996 Percent
Tested by:	CANMET	Univ. of Missouri - Rolla
Carbon	0.20%	0.21 %
Sulfur	0.065%	0.069%
Manganese	0.52%	0.47 %
Phosphorous	0.01%	0.045%
Silicon	0.025%	0.017%
Copper	0.026%	0.024%
Nitrogen	0.004%	0.0035%
Oxygen	-	0.013%
Manganese-Sulfur Ratio	8.0:1	6.8:1

Table 3

Tensile Tests Results

Yield Strength	=	38,000 psi (262 MPa)
Ultimate Tensile Strength	=	62,500 psi (431 MPa)
Percent Elongation	=	29%
Gage Length	=	1 inch (25.4 mm)
Specimen Diameter	=	1/4 inch (6.35 mm)

in a television interview in October 1993. She had hopes that the stern would break away and float, possibly saving her father's life. However, between 0215-0220, the darkened stern began rose again and then began sinking below the surface. Chief Baker Charles Joughin, who was at the ensign staff at the stern end, later testified that it was like riding an elevator down to the water. With the absence of suction forces, he was able to swim away without even wetting his hair. This account indicates the swiftness of the stern's demise.

Edith Russell, in a lifeboat near the sinking site, later provided evidence in an interview with "Ladies Home Journal" in May 1964 that before the ship went down... "there was a huge roar from her, like one clearing his throat" This sound continued for a few minutes. She also noted that immediately after the ship sank, there was a heavy explosion, followed quickly by a second and a third. The welling up of water over the sinking site actually pushed her lifeboat further away from the sinking site.

Events Below the Water Surface. It cannot be known with any certainty what happened to the ship during its descent to the seabed. However, once the *Titanic* disap-peared below the water surface, the ship broke into three pieces. The depth where these events occurred cannot be estimated with any precision. Many compartments in the stern did not have time to equalize pressure, as the stern section was being pulled down rather quickly by the bow portion. Implosions began at different times in the stern compartments, depending in each case on the strength and tightness of the surrounding structure. There is convincing evidence, based on surveys of the stern wreck, of serious implosion in the area of the refrigerator spaces and cold rooms that greatly weakened the stern structure. Entrapped air was suddenly expelled by the intense water pressure, curling back the deck structure over this area.

The buoyancy of the stern piece also appears to have resisted the downward pull of the bow. This ultimately led to the separation of the bow portion, followed by the third or double bottom piece.

Terminal Velocity during the Sinking Descent. There is very little data on the terminal velocities of sinking ships. However, German designers of the nuclear-powered cargo ship *Otto Hahn* were concerned with the problem of this ship sinking and the implosion of the nuclear reactor compartment [9]. Experiments were conducted at the Hamburg Ship Research Institute on a 70:1 scale model complete with all of its watertight subdivision. Models of other ship designs were also tested for comparison purposes. Various sinking sequences were tried to duplicate all possible situations, with the models attaining terminal velocities of 14 to 15 meters per second. These experiments provided the following generalizations:

- Sinking speed is a function of a ship's weight and air volume entrapped in the hull.

- At a certain depth a ship will revert to its upright position from a trimmed or capsized attitude.

- The size of superstructure reduces the sinking speed. The lowest sinking speed was attained in these tests with ships that had superstructures from the bow to the stern.

- Sinking speed is initially greater in ships with large cargo holds, but with sufficient sinking depth this should equate to that of ships with smaller compartments.

These tests gave us some insight as to what may have happened to the bow and stern sections of the *Titanic*. The stern portion had entrapped air before implosion and would have a slower initial sinking speed than the bow which had completely filled with water. However, the bow portion had more superstructure, which would have slowed its speed of descent. There is no doubt that the bow portion pulled the stern down to an implosion depth and at that point the two sections separated, with the double bottom section still attached. At some unknown depth, this would fall away. The stern sustained much damage from the implosion and its plunge downward. Its mass was such that it may have hit the sea bed with a velocity of no more than 45 knots causing severe shock damage to an already weakened structure. Based upon tests with the *Otto Hahn*, we estimate that the bow section had a terminal velocity of 30-35 knots. There may have been some downwash effects, but these would have had a minor impact on the wreck because the velocity of descent would have caused the major damage. We also believe that the bow glided down and struck the seabed at angle of no more than 30 degrees. The after end of the bow section, more massive, was forced downward by the abrupt impact. This caused further buckling of plate and popping of rivets making it more difficult to distinguish sinking damage from that of bottom impact.

As the stern continued its descent, the only portion not grossly affected by the forces of the sinking was the area of the aft peak tank, where the frame spacing was 2 feet and the structure rather stout. The failures there would have been in the lighter deck or bulkhead structure bounding these tanks within the ship that allowed the entrapped air in the peak tank to escape. The stern end probably became the leading edge as it was a more hydrodynamically efficient in this capacity and created less drag forces than the forward part of the stern structure. However, the increasing water pressure on weakened structure may have further compressed the side shell and deck structure over other structures or equipment such as the two remaining aft cylinders of both reciprocating engines. In other areas, the plating was bent back like an opened sardine can and the flow of water past weakened structure may have caused further damage. This accounts for the junk pile appearance of the stern portion of the wreck. When the stern hit bottom at the estimated speed of 45 knots, it was an abrupt impact, unlike the bow, which glided down. The rudder knifed into the sediments and David Livingstone and Bill Garzke believe that the outer shafts were bent upwards as the propellers and shafting were pushed down into the sediments by the force of impact. The shock forces associated with this impact were sufficient to cause additional damage to weakened structure. Sonar scanning of the outboard shafts might determine the degree of damage to the outboard shafting.

Steel Metallurgy Studies. Chemical tests of the steel samples brought back by the 1996 Expedition show a low residual nitrogen content. This confirms that the steel for the *Titanic* was produced by the open hearth rather than the Bessemer process. In the open hearth process, a pool of molten pig iron and scrap steel rests in a furnace lined with refractory brick. During the steel making process, the pool of molten metal is exposed to an oxidizing atmosphere to remove the excess carbon and silicon from the pig iron leaving a low to medium carbon steel. The refractory brick can be silica brick (acid) or basic brick, such as calcined dolomite (CaO.MgO). The basic lining has the advantage that phosphorous and sulfur in the molten metal will react with it to form phosphates or sulfides that rise to the surface of the molten metal and enter the slag floating on its surface, thus reducing these two elements in the steel. The impurities, sulfur and phosphorous in steel, will lead to low fracture resistance, commonly viewed as embrittlement. High oxygen content, which is present in the form of oxides, will do the same. The manganese-sulfur ratio of the hull steel recovered from the wreck site was determined to be 6.8:1, low by present standards. Modern steels, particularly those produced after 1947, may have a ratio as high as 200:1. The sulfur content of the steel was at the top end of what is considered acceptable for a modern mild steel to be used in shipbuilding. The low sulfur to manganese ratio has two effects. One is the previously mentioned higher sulfur content, and the other is reduced manganese. Manganese is added to the steel to bind the residual sulfur as manganese sulfide precipitates, which will be randomly distributed. If there is insufficient manganese, the sulfur will combine with the iron to form the ferrous sulfide, preferentially at grain boundary intersections, and this creates paths of weakness for fractures. However, the SIMS data showed that the sulfur was bound in the particles, so the amount of manganese was sufficient to do the job. Manganese is also a powerful solid solution toughening agent. Generally, the maximum toughening effect from solid solutions of manganese occurs at roughly four times the amount found in the steel recovered from the Titanic. In addition, the steel used in the hull of the *Titanic* is referred to as a semi-killed steel because it had been partially deoxidized after the excess carbon and silicon were oxidized, prior to casting into ingots.

Davies[12] recently published historical data showing that at the time of the construction of the *Olympic*-class liners, 75% of the open hearth steel produced in the United Kingdom was made in acid-lined furnaces. The high sulfur and phosphorous content in the steels brought back by the 1996 *Titanic* Expedition indicates that an acid open hearth furnace was probably used in its production. The principal steel suppliers to Harland & Wolff during the construction of the *Titanic* were Dalzell and D. Colvilles & Co., Motherwell Works. These steel mills also produced the steel used in the construction of the HMS *Hood* and the RMS *Queen Mary* by John Brown & Co., Clydebank.

To confirm theories thus far advanced on the hull failure, a hull plate from the bow area of the wreck and a plate from a major transverse bulkhead were brought to the surface in August 1996. A piece of a channel beam was recovered from the stern. The plate and stiffeners were tested for tensile strength, microstructure, and hardness at the University of Missouri-Rolla and at the laboratories of Bethlehem Steel, Bethlehem, Pennsylvania and National Institute of Standards and Technology (NIST). Although many factors in the loss of the *Titanic* have been examined over the years, the metallurgy of the steel was not given a thorough analysis in the absence of evidence. In 1991,

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12 Reference [10], p. 14.

however, the IMAX Expedition brought back some hull steel for testing and it was found that the steel fractured in a brittle mode at the nominal service temperature of -1° C. With the steels recovered during the 1996 *Titanic* Expedition, Panel SD-7 instructed the metallurgists to do the following:

1. Examine the mechanical properties of the steel - Charpy V-Notch Test.
2. Determine the chemical make up of the steel including such elements as sulfur, oxygen, phosphorous, carbon, manganese, nitrogen, and other elements.
3. Examine the steel's microstructure.
4. Determine the steel's strength by tensile testing.
5. Determine the steel's ductile-brittle transition temperature.

The Charpy impact test was developed in 1909 to simulate the rapid loading that often occurs in equipment and machinery operation, in contrast to the slow loading observed in tensile tests. The American Society of Testing Materials (ASTM) accepted a provisional standard for the Charpy test in 1933. Charpy specimens were prepared from the *Titanic*'s hull plate. Since optical micrographs indicated that there was severe banding in the steel, it was inferred that the mechanical and impact properties may have been dissimilar in different directions of the hull plate relative to the rolling direction. The banding was actually caused by a heterogeneous distribution of impurities (see Figures 2 and 3). This effect has to do with the direction in the steel relative to the rolling direction. Because steel plate is much longer than it is wide, rolling occurs in only one direction.

Two groups of Charpy specimens were prepared so that in one group the long direction of the specimens was parallel to the longitudinal direction of the hull plate and in the second group the long axis of the specimen was parallel to the transverse direction. Figure 4 compares experimental results from the Charpy impact test of the *Titanic* hull steel for the longitudinal and transverse rolling directions with a modern ASTM A 36 mild steel. Using 20 foot-pounds for the determination of the ductile-brittle transition temperature, the transition temperature was -15 °C for the modern A 36 steel, while the *Titanic* specimens yielded transition temperatures of +20 °C for specimens in the longitudinal direction and 30 °C for the transverse direction. The transition temperatures for the *Titanic* steel are much above the water temperature of -2 °C at the time of the ship-iceberg collision. Figure 4 also shows that the *Titanic* steel has approximately one third the impact strength of a modern A 36 steel, but at the temperature of water in which the ship sank, the steel was at its Charpy lower shelf of absorbed energy. It should be noted that in current shipbuilding practice A 36 steels is limited to thinner plate thicknesses. In addition, the lack of toughness in the *Titanic* steel, as illustrated in this report, is not surprising considering latter day knowledge of steel metallurgy and grain structure.

The chemical tests of the steel, summarized in Table 2, indicated higher percentages of sulfur, phosphorous, and oxygen than would be permitted by classification societies rules in modern mild steel plates or stiffeners. The differences in chemical analysis are due to variability in steel production. The results of the 1996 analysis of the hull pieces have also been compared with the 1991 tests of a hull piece done by CANMET of Ottawa, Canada. The tests done by CANMET and the University of Missouri - Rolla, on the two different hull plates show remarkable agreement in the percentages of the steel's major elements, with the exception of phosphorous. This can be attributed to the chemical testing or a different source of iron ore used by the steel mill. Certain European iron ores are known to have higher percentages of phosphorous than others. CANMET did not test for the oxygen content, but good present-day practice is to have the oxygen level at no more than 0.01%. Excess oxygen in the steel ingot has the tendency to form precipitates which also can embrittle the steel. Dissolved oxygen will also drive the transition temperatures to higher values.

The sulfur content of this steel is important in understanding the fracture mechanics of the hull failure of the *Titanic*. Sulfur and manganese react to form manganese sulfide. Without manganese, the steel would have iron sulfide formed at the grain boundaries. The iron sulfide has a low melting point so the steel ingot would have a grain boundary envelope which, at rolling temperatures, would be molten. Since a liquid phase will not resist shear stresses, hot work (e.g.: by rolling) would

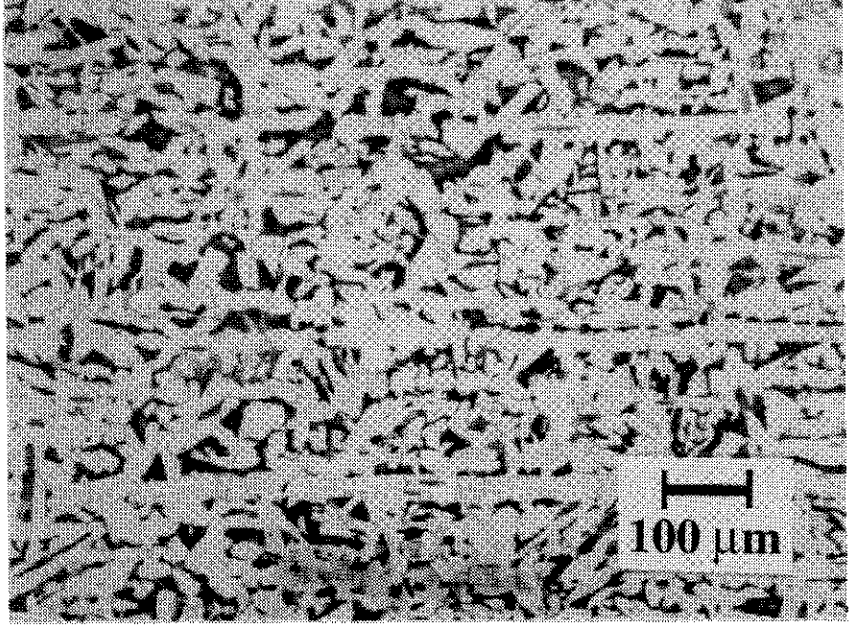

Figure 2

An optical micrograph of the *Titanic* hull plate in the longitudinal direction.

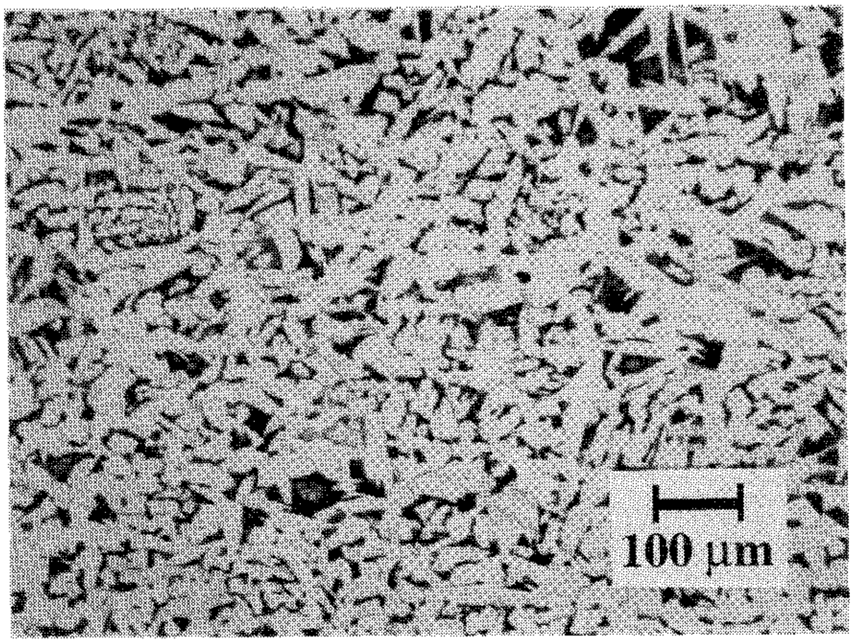

Figure 3

An optical micrograph of the *Titanic* hull plate in the transverse direction.

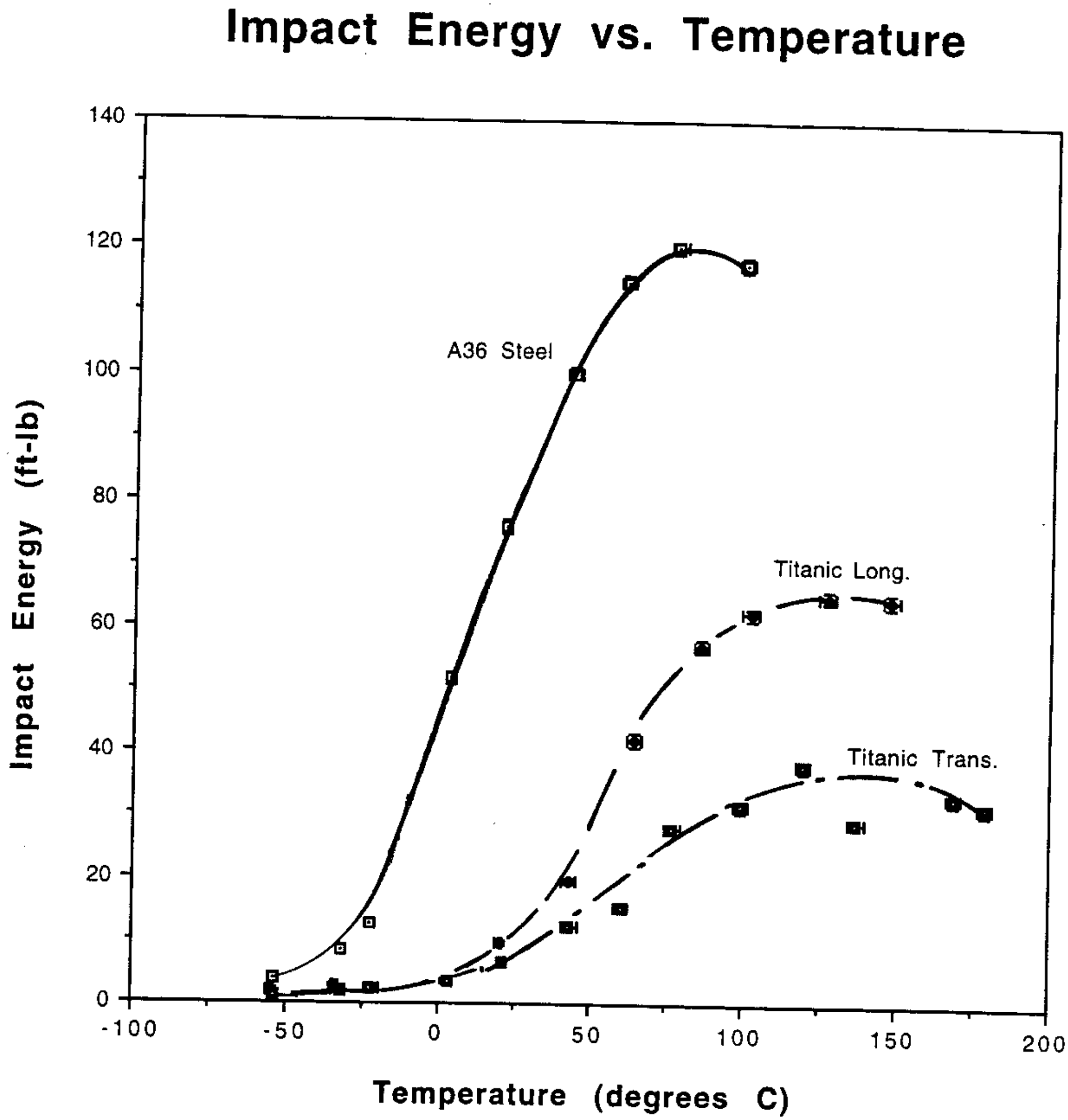

Figure 4

Charpy V-Notch Test of *Titanic* Steel Versus a Modern A 36 Steel fracture the ingot containing FeS whereas the solid, distributed, MnS phase prevents hot work fracture (known to steel makers as "hot-short"), but will create stringer-like inclusions in hot-rolled plates or shapes. While undesirable, that is better than "hot-shortness". Such slag-like inclusions in the microstructure will be planes of weakness for stresses transverse to the rolling direction. These inclusions also form avenues of failure along which plates will break in a straight line under high stress concentrations as occurred with the *Olympic* (see page 38, Reference [4]). Steel metallurgy in the early 1900's was unaware of these problems. It was not until 1947 that the right proportions of the minor elements in steel were known. They have been regulated by all classification societies since then.

It was not until around 1930 that ship classification societies disallowed the cold punching of rivet holes in steel plate - rivet holes had to drilled and reamed. The steel used in the *Titanic* was the best available in 1909-1914 when the three *Olympic* class passenger ships were built. However, the mechanics of ductile-brittle behavior were not known until unexplained failures in Liberty ships and T-2 tankers during World War II were finally understood in postwar analyses. Although steel quality did not cause the *Titanic* tragedy, it certainly contributed to the hull failure. The sulfide particles under stress may nucleate micro-cracks. Further loading will cause micro-cracks to coalesce into macro-cracks which then link up with the main cracks, enabling fracture propagation. This is the method of failure in the shell plating of the *Titanic*. The deck plates, on the other hand, had their inclusions in a different plane to the main stress flow and the lower decks were of a finer grain structure because of the rolling mill action. The decks' failures were more ductile and resembled a "woody" failure due to a slower rate of loading.

The metallography of the *Titanic* steel was done with a scanning electron microscope. The steel was fairly typical of steel containing 0.20% carbon, but the grain size of the steel was determined to be quite large, reducing the strength and ductility of the steel. Figures 2 and 3 show a scanning electron micrograph of this steel and large dark gray areas of ferrite, a low carbon phase. The ferrite particles are separated into grains by their respective grain boundaries. The lamellar structure is pearlite, a two-phase eutectoid mixture consisting of ferrite (the dark areas) and cementite, Fe_3C (the lightly colored areas). The large circular region can be shown to be a nodule of manganese sulfide. The microstructural analysis showed that the grain structure of the *Titanic* steel was very large. Therefore, the coarse grain structure of the semi-killed steel made it easier for cracks to propagate, while the chemical analysis showed the further weakness in the steel from manganese-sulfide inclusions.

Table 3 gives the yield strength, the ultimate tensile strength, and percentage elongation at failure of the hull specimen from the *Titanic*. The values of yield strength and the ultimate tensile strength are typical of what would be observed for a low-carbon steel of this composition. The percentage elongation is a little smaller than might be expected for a mild steel. The low manganese sulfur ratio, shown in Table 2 for both the CANMET and University of Missouri-Rolla analyses, and the large grain size might account for the quantity.

There is some indication of brittle fracture of steel plates in some of the *Titanic*'s plate wreckage, but not in all. Even though brittle steel has reduced ductility, there is a fair amount of ductility in some of the hull plates of the *Titanic*. This ductility also definitely depends on the rate of loading. It would appear that steel failures were due to a number of factors. The most important of these is the flooding that created such a large bending moment in the hull that the resultant stresses in the plates around the second of only two expansion joints grossly exceeded the yield strength of the steel. In fact, the 4 by 7 meter "Big Piece", which was from an area aft of this joint and near the termination of the fracturing.

The factors contributing to the break up of the *Titanic* were the steel grain size, the oxygen, sulfur, and phosphorous contents in the steel, and the cold punched riveted holes that were not reamed to remove micro cracks. Many of the rivets were hydraulically driven which added to the stresses on the plates where the rivet heads made contact. Also significant in the failure of the steel was its relatively low ductility at the freezing temperature of water. In Figure 4, the *Titanic* steel shows a much higher ductile-brittle transition temperature than the A 36 mild steel used for the test comparison. More significantly, at temperatures near the freezing point of water, it loses almost all of its ductility, whereas the A 36 steel retains part of its ductility. However, no modern ship, even a welded one, could have withstood the forces that the *Titanic* experienced during her break up on the night of 14-15 April 1912. They were simply beyond those used in the design of passenger ships. Obviously, the residual strength of the steel was exceeded when some 39,000 tons of flooding water entered the bow portion of the ship. Fracture in the deck plates was more a case of plastic collapse and ductile failure. Fracture in the shell plates with their coarser grain structure and impurities resembled brittle fracture, but there was a significant plasticity in some of the plate, for example at the "big bend".

Results of tests done at the University of Missouri - Rolla were corroborated by Dr. Harold Reemsnyder of Bethlehem Steel Corporation and Dr. Timothy Foecke of NIST. In addition, Dr. Reemsnyder was provided with samples from the *Nomadic*, one of the tenders built in 1911 to service the *Olympic* class liners in their port calls at Cherbourg. (The *Nomadic* still exists in Paris, France as a floating restaurant. Although closed for alterations, the owner plans to reopen the ship soon again.)

Important in the analysis of the *Nomadic*'s steel was the chemical test, which showed a higher percentage of sulfur and oxides than would be permitted in modern steels, although the grain size was approximately one-third that of the hull steel from the *Titanic*. The smaller grain size of the tender's steel sample may be attributed to the greater reduction in thickness at the steel mill since this steel was 0.25 inches thick compared to 1.0-inch for the *Titanic* plate. The *Nomadic* mild steel plate, however, shows surprising correlation in tensile strength with modern mild steels (see Figures 5 and 6).

Materials Tests. The chemical analysis of a side shell plate brought back from the wreck site in August 1996 shows a higher percentage of sulfur than is permitted by classification societies currently in the construction of ships. The sample also showed higher percentages of phosphorous and oxygen by those same standards.

The Charpy V-notch and tensile tests were conducted with eight specimens from a sample of present-day A 36 steel for comparison to steel from the *Titanic* brought back in August 1996. These were also compared to tests done on a similar sample of hull steel brought back from the IMAX 1991 Expedition. The tests show that the *Titanic* steel has low impact strength and 5% ductility, particularly at the temperature of 0 °C. The analysis done by the Canadians at CANMET and the Canadian Defense Laboratory show 100% brittleness at 40°C.

After the T-2 tanker *Schenectedy* broke in half while tied up at her fitting out pier in Portland, Oregon on January 16, 1943 and several more ship casualties involving Liberty ships occurred, a major investigation was undertaken by the U.S. Coast Guard. This investigation was soon was joined by advisory groups from the U.S. Navy, the Maritime Commission, and the American Bureau of Shipping. Guidance was also sought from the War Metallurgy Committee and the National Bureau of Standards (now part of NIST) did some of the examination and testing.

Steel samples were taken from ships and subjected to visual and dimensional studies to characterize the fractures from the perspective of the sample's location, the ambient conditions including the temperature of the plates, and the loading condition of the ship at the time of fracture. The steel was examined for grain size and other metallurgical features, and a chemical analysis of the steel plates with brittle fracture was performed. This program lasted for approximately 12 years and was guided to completion by the Ships Structure Committee. By 1958, 149 samples had been collected which could be reported as part of a statistical analysis. Specified tensile testing of steel showed that the hull steel met the required standards of that time. Furthermore, variations in the tensile properties showed no correlation with the propensity to fracture. In contrast, the Charpy V-notch impact tests revealed a statistically meaningful correlation with fracture initiation.

One conclusion from these studies [11] was that phosphorous, even though present in small amounts in a steel, had a pronounced effect on the initiation of a fracture, particularly if the plate had been welded or flame cut. It is important to note that the *Titanic* steel brought to the surface in August 1996 had a significant percentage of phosphorous and that the V-notch transition temperature was elevated. The grain size was very large, although a decrease in plate thickness and grain size in steel plate from the *Nomadic* decreased the transition temperature in comparison to the *Titanic* steel. It should be noted that the hull steel analyzed by CANMET from the 1991 IMAX expedition shows a much smaller amount of phosphorous. There was a heat-to-heat variability in the chemistry and plate-to-plate variability in the mechanical properties of the steels purchased by Harland and Wolff for the *Olympic*-class liners which required a large amount of steel in their construction. These variabilities were the direct result of tolerances in chemistry and thermo-mechanical processing during the period that these ships were built. Further, quality control in the production of steel in 1910 was not as good as it is today.

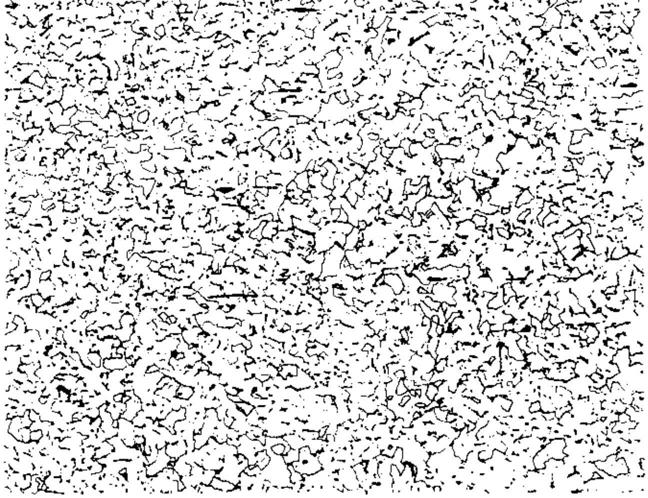

Figure 5

Nomadic Plate, Longitudinal Optical Micrograph

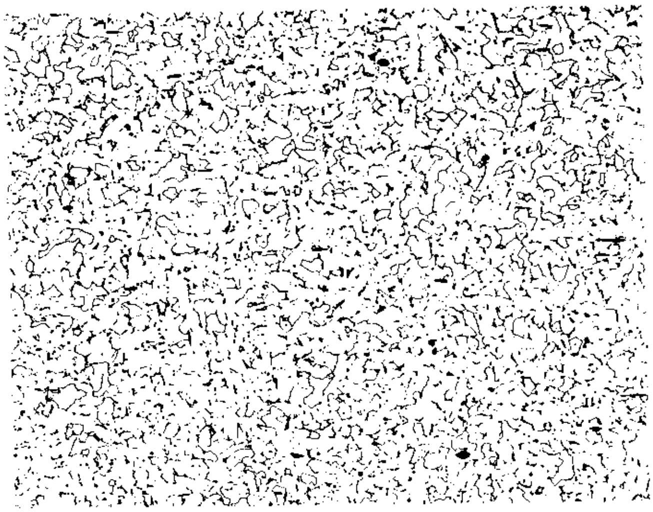

Figure 6

Nomadic Plate, Transverse Optical Micrograph

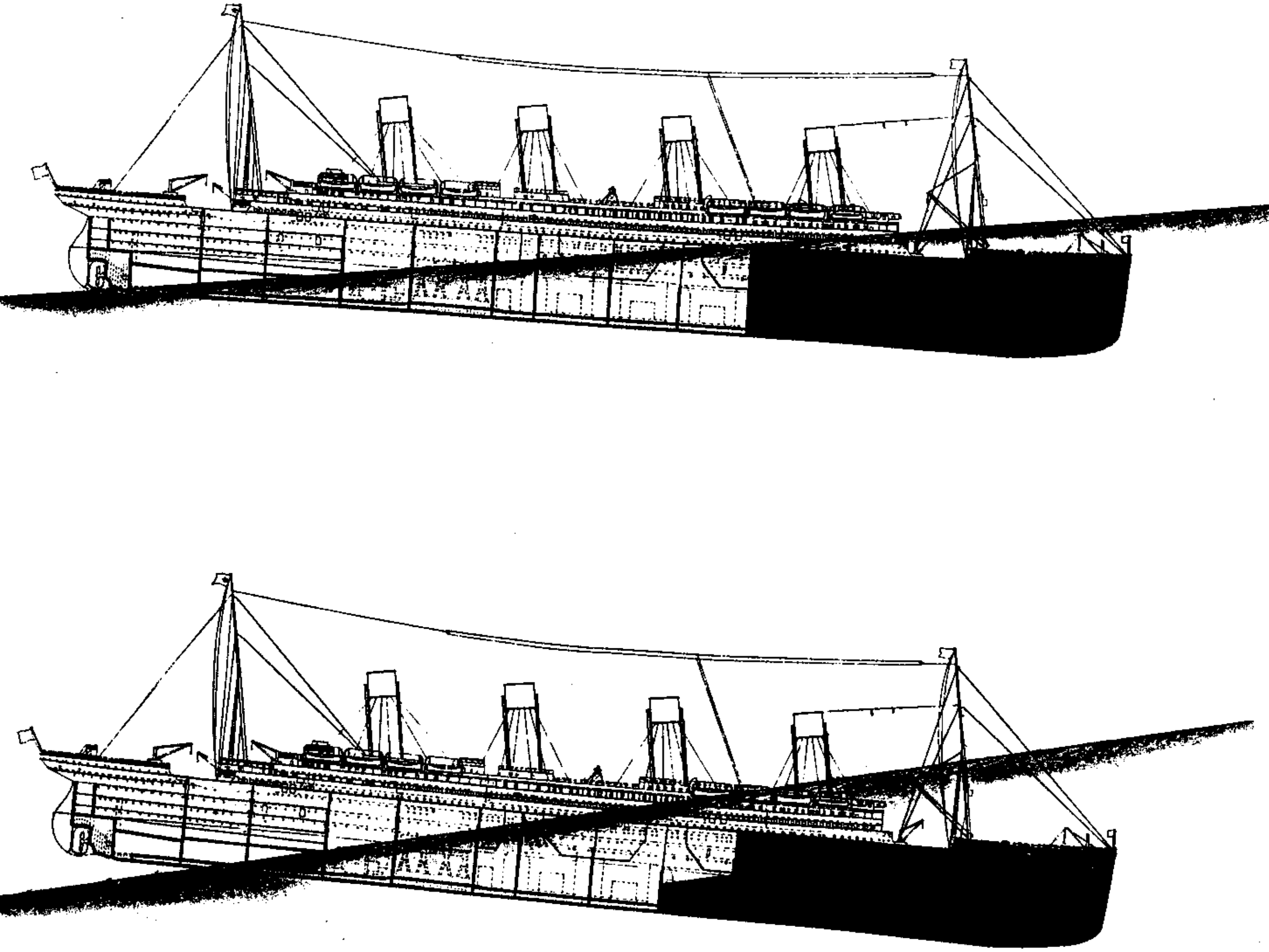

Figure 7

The flooding diagrams of Conditions C-6 and C-7 from Reference [5].

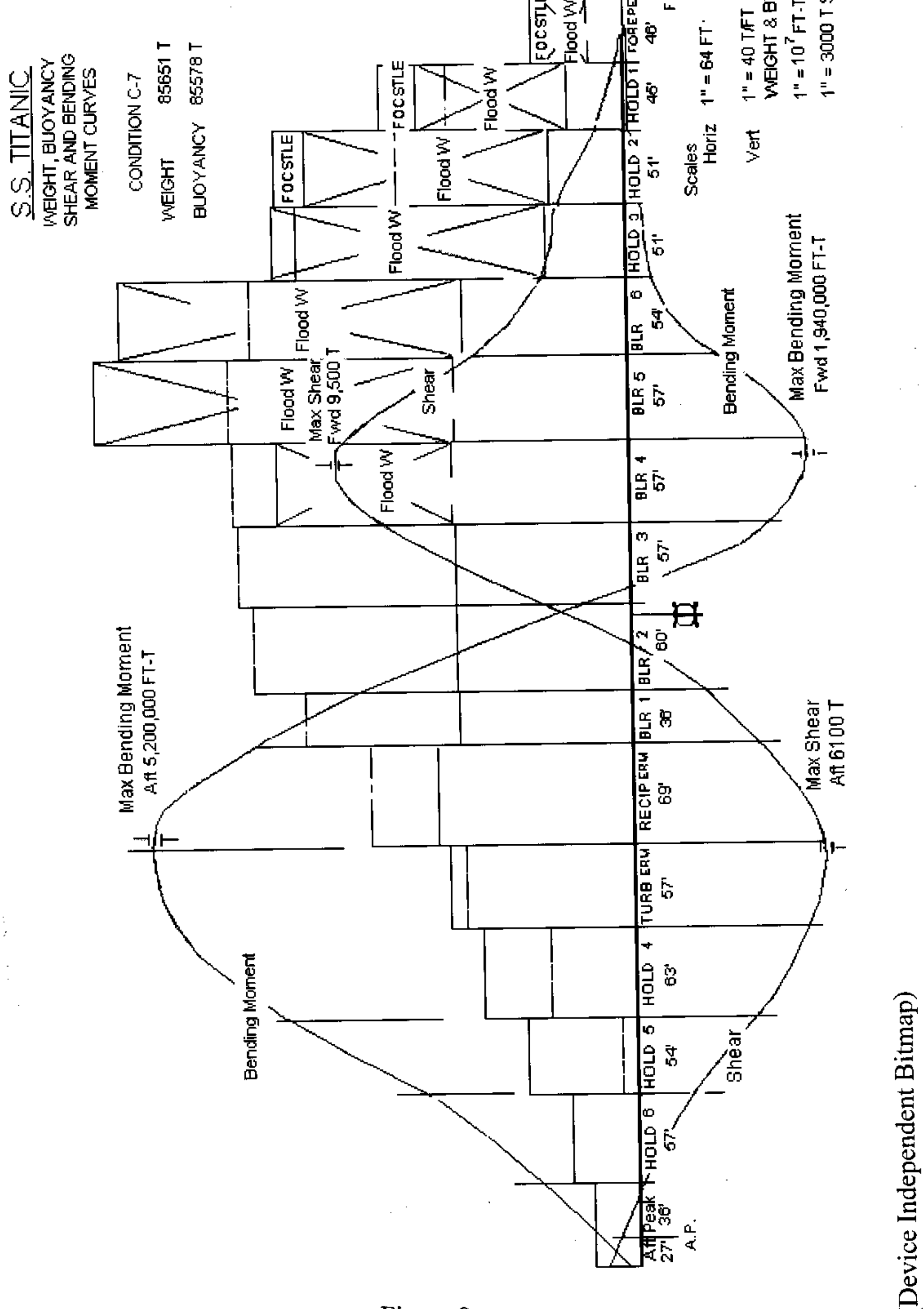

Figure 8

Load, Shear, and Bending Moment Curves, Condition 6 of Reference [5].

Stress Computations. To determine the possible stress levels just before the ship fractured, author Arthur Sandiford computed the section modulus based on the intact structure from the 1926 structural data of the *Olympic* provided by John Bedford, the retired chief naval architect of Harland & Wolff. Adjustments were made to eliminate the inner side shell added to her after the *Titanic*'s loss. One value of section modulus was used for all conditions to be studied even though there were slight variations in the location of the maximum bending moments and section modulus values as the ship progressively sank. Also, only 80% of the bottom structure, which includes the inner bottom, bottom shell plating, the bar keel, the center vertical keel, and the margin plate, were considered no longer effective. This accounts for the changing structure as the hull was being compressed during the sinking process.

The bending moment used for the stress computations came from Reference [5]. Three conditions were selected for this analysis, two of those correspond to Conditions C-6 and C-7 from that reference, plus an intermediate one of our own that was transitional to Conditions C-6 and C-7. These conditions show the flooding in the ship just before she sank.

The values for the bending moment and shear diagrams were done for three flooded conditions, ultimately with the forecastle and the forward portion of C Deck submerged (see Figure 7 from Reference [5]). The results are tabulated in Table 1.

The flooded spaces were identical to those used in the Hackett and Bedford papers [5]. Some of the flooded capacities of the spaces were changed due to revised permeability assumptions and calculated volumes. For example, the volume of the forecastle was based on the deck area from the 1911 arrangement plans and an 8.5-foot deck height was used to calculate the volume.

The weight and load distribution curve was prepared by dividing the weight data into sections by watertight compartments - 16 in all. Flooding water was added to the weight curve and separated as described above for the weights and loads. The same procedure was applied to the buoyancy curve of the hull that was developed from a previously prepared body plan.

Figure 8 shows the bending moment, shear, and load curves for Condition C-6 that correspond to the time period between 0150 and 0205 when Boiler Room No. 4 was in the process of flooding. It is believed that the high bending stresses, combined with the high shear loads began to destroy the structure over the Reciprocating Engine Room. In addition, this was an area where there were large openings for stairwells, uptakes, intakes, and engine access. The bottom structure was strained by a high hydrostatic head of 67 feet, almost double the normal load draft.

The immersion of C Deck and the commencement of flooding in Boiler Room No. 4 very rapidly increased the stresses in the main hull girder. Within a matter of minutes, the calculations by Sandiford indicate that the stresses went beyond the yield point of the steel, particularly in areas of structural discontinuities, such as the expansion joint and large openings. These localized regions of high stress may have become regions of structural failures and fractures. Once plate fractures occurred in the hull, crack propagation could have quickly spread across the strength deck and down the side shell. In such a scenario, fracture of the hull girder would be eminent.

The trims associated with these conditions were greatly dependent on the position of the longitudinal center of gravity. The authors wish to acknowledge the assistance of Mr. John Bedford who provided us with the boiler liquid weights, coal consumption rates, and the reduction of the water in the boilers that helped determine the condition of the ship during time before she sank.

After the hull girder experienced its failure and the transverse bulkhead collapsed, the main transverse watertight bulkhead between Boiler Room No. 1 and the Reciprocating Engine Room was torn out of the ship along with the five single-ended boilers in Boiler Room No. 1. and pieces of the side shell above the inner bottom level.

It was discovered in the 1996 IFREMER (Institut Francais de Recherche po l'Exploitation des Mers) and RMS TITANIC, Inc. Expedition to the *Titanic* that the two forward cylinders from both reciprocating engines and the forward end of the main bed plate were missing from the ship. The fracture through the stern portion passed right through these two engines. A piston rod and cam shaft have been recovered from the debris field, confirming the fact that the end of the *Titanic* was indeed a violent one. These engines weighed over 400 tons apiece and were four stories high. A marvel for their time, they were a specialty of Harland and Wolff and served in the *Olympic* for 25 years without any major mechanical problems. These failures show the magnitude of the forces involved in the break up of the *Titanic*. The cast iron bed plates of the reciprocating engines, while thick, were inherently brittle. Cast iron can withstand compressive stresses, but the cast iron bed plate of these engines could not withstand the unusually large bending forces inherent in the ship's break up. Therefore, it was no impediment to the bending forces involved when the inner bottom buckled. Canadian tests of cast iron from equipment in the wreck have shown that the cast iron specimens were very brittle. This type of engine was not very well connected at the top of the cylinder head, but relied on the rigidity of its bed plate.

Conclusions from the Analysis. The most important conclusion of this analysis is that sinking of the *Titanic* was inevitable. There simply was no way to save this ship. With the side shell damaged in more than six compartments during the iceberg-ship collision, those compartments flooded at different rates. Once all the bow compartments flooded, the water began flooding into other compartments through openings in the deck structure where it could make access. By 0200, there were over 39,000 tons of water in the ship. She was not designed to resist the massive forces brought about by this inflow of flooding water.

Although Boiler Room No. 4 was initially taking some water, flooding there was controlled by a bilge pump in this space. We believe that the final phase of the sinking began when the non-tight coal bunker bulkhead at the forward end of Boiler Room No. 5 failed. After resisting a head of some 25 feet, which exceeded its design limits, the bunker bulkhead failed almost one hour after the initial impact of the iceberg.

One question emerges from the discovery of the wreck in 1985-86 concerning the ship's sinking phase, "Did she break apart at the surface or sink intact?" To help address that question, a finite element analysis was conducted by Gibbs & Cox, Inc, and the results compared to survivor testimony. (See Table 4, a tabulation of survivor testimony). The analysis supports other evidence that the ship likely began to fracture at the surface, and that was completed at some unknown depth below the water surface. The resulting stress levels in the strength deck below the root of the second expansion joint (aft) and in the inner bottom structure directly below were very high due to the unusual flooding occurring in the forward half of the ship. These patterns of stress, which help indicate regions of the hull girder which sustained significant stress, now supports the argument that the hull failed at the surface and broke into three parts during the plunge to the seabed some 12,000 feet below. Although all of the officers testified that the ship sank intact, some survivors and a few crew testified to a hull failure at the surface. The most vocal of the passengers were 48-year old Elmer Z. Taylor, a mechanical engineer and 17-year old John Thayer, Jr., who had someone make drawings for the Philadelphia Bulletin of what he thought he saw when the *Titanic* sank. Seven-year-old Eva Hart, who saw the settling of the stern, had hoped that it might float, thereby saving the life of her father. Elmer Taylor, who was in Lifeboat Number 5 and close enough to the ship to observe her final demise, later wrote:

> "The cracking sound, quite audible a quarter of a mile away, was due, in my opinion, to tearing of the ship's plates apart, or that part of the hull below the expansion joints, thus breaking the back at a point almost midway the length of the ship."

Certainly some pieces of wooden wreckage later retrieved from the site of the sinking (particularly, a delicately carved oak piece from the forward entrance to the First Class Lounge), cabin fittings, mahogany drawers and cork insulation from ruptured bulkheads gave evidence to the violent forces associated with the hull failure.

Quartermaster Walter Perkis in Lifeboat No. 4 noted a cracking noise around 0200 when he rowed by the area of the second expansion joint, which was located between the third and fourth funnel. He thought this was dishes breaking in the galley as the stern began to upend. However, brittle or ductile fracture of steel plate creates lots of noise. Depending upon the amount of steel, it could resemble the breaking china plate or even a rifle shot. In fact, the noise of a brittle fracture can be quite loud as happened with the tug-barge *Martha Ingram* when her hull failed from a brittle fracture in Port Jefferson, New York in February 1972.[13] When 6-foot wide HSLA-80 plates were tested for ductile failure at Lehigh, there was no way to prepare for the sound - everyone jumped.

The use of a sub-bottom system to scan along the bow and a side scan sonar over the debris field was important in the analysis of this wreck. For the first time, we were able to see the magnitude of the damage to the starboard bow. The side-scan sonar located the missing center section of the hull. These two tools can be very valuable in the analysis of recent ship casualties like the SS *Derbyshire* or *Edmund Fitzgerald,* where ship debris or fragments are hidden below sediments or cargo the ship was carrying. They would also be useful in further damage analysis of the German battleship *Bismarck* to determine the location of torpedo hits. The photo encounter of the 1989 Ballard Expedition was hampered by the fact that this battleship was immersed

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13 Catastrophic hull failure due to brittle fracture caused by a lack of material toughness is a rare occurrence and the *Martha Ingram* is the most recent case known to the authors.

in sediments up to her design waterline. Thus, the holes made by torpedoes, if they exist, could not be precisely determined. Sub-bottom scanning could peer through these sediments.

Results of the Finite Element Analysis. Gibbs & Cox, Inc. was jointly funded by the Discovery Channel and the Society of Naval Architects and Marine Engineers, to conduct a very basic study of the break up of the RMS *Titanic* via linear finite element analysis. This was done in conjunction with some materials testing of the *Titanic* steel by the University of Missouri-Rolla, with advice and suggestions from Professor H.P. Leighly Jr., Dr. Timothy Foecke of the National Institute of Standards and Technology (NIST), an adjunct of the U.S.Department of Commerce, and Dr. Harold Reemsnyder of Bethlehem Steel Corporation, Homer Research Laboratory in Bethlehem, Pa. Professor Leighly provided a graphical Charpy V-Notch Impact Test curve of absorbed energy as a function of temperature that was helpful to the analysis. That relationship is shown as Figure 4.

The Finite Element Model. With the discovery that the *Titanic* hull was in two pieces in 1985, theories abounded on how the ship broke apart during the sinking process. This was further intensified when Dr. Ballard revisited the wreck site in 1986 and found that there was a missing 17.4-meter section in the midships region of the ship. Even during the American and British inquiries into the disaster, few questions focused on the structural aspects of the ship and how it may have failed at the surface before its plunge to the seabed below. Despite a few of the survivors' testimonies (see Table 4), it was concluded that the ship sank intact. With the discovery of the ship in two parts, research began to address how this could have happened. Subsequently, the Discovery Channel proposed a stress analysis to help determine the possibility of hull fracture at the surface.

Engineers have been analyzing the stresses in ship hulls using the finite element method as far back as the 1960's. However, advances in computer technology have dramatically improved this technique. The stresses in the *Titanic* were analyzed as the flooding progressed within the bow, using modern finite element techniques that were not available until the 1960's and certainly were not known to the structural designers of the ship at the turn of the twentieth century. A full-ship model was graphically constructed, using much the same modern approach as for USN destroyers and cruisers today. Loadings for the model were developed using one flooding scenario from the paper, "The Sinking of the *Titanic*", by Chris Hackett and John C. Bedford [5]. The corresponding weight and buoyancy curves, developed by Sandiford and Garzke, were used to model the critical flooding condition believed to represent the hull loadings just prior to hull fracture. Since the flooding process took place over several hours, it was assumed that a quasi-static analysis would be appropriate. The initial modeling effort focused on the determination of the location and magnitude of high-stress regions that developed in the hull while she remained on the surface.

It was determined that stress levels in the midsection of the ship were at least up to the yield strength of the steel just prior to sinking. Figure 9 is a contour plot of stresses in the *Titanic* hull girder just before Boiler Room No. 4 flooded. When considered alone, stresses at these levels do not indisputably imply catastrophic failure. Additional analyses, focusing on probable locations of initial hull fracture, are required to indicate that the ship sustained possible catastrophic failure at the surface and began to break apart. It is noted that significant stresses were developed in the vicinity of the two expansion joints, and in the inner bottom of the ship between the forward end of Boiler Room No. 1 and the aft end of the Reciprocating Engine Room. Structural discontinuities, such as expansion joints, result in stress-concentration development. Typically, stress concentration levels are three to four times that of free-field stresses. While these structural discontinuities have not yet been thoroughly investigated, it is anticipated that stresses developed at these locations were significantly higher than the material yield stress.

In time, engineers hope to be able to further investigate local design details suspected of failure. The hull ruptures that were identified by Harland & Wolff's David Livingstone during his undersea dives provided valuable insights into this effort. The persistent question is whether these hull ruptures occurred at the surface, as a result of progressive flooding, or near the bottom as the result of implosions or explosions from collapsing machinery. Sonar imaging of the debris field by Paul

Table 4
Tabulation of Survivor Reports

Survivor Name	Age	Iceberg Encounter	Ship Breakup
Elmer Z. Taylor (Passenger)	48	There was a terrible shock that made the ship tremble from stem to stern. Went up on deck and saw ice all over the deck.	Was in Lifeboat #5 and was evacuated in first hour when survivors not accessing boats. Observed ship breakup and wrote about brittle fracture of steel (see page of text)
John Thayer, Jr. (Passenger)	17	None	Was on the Boat Deck and was thrown into water when the bow plunged down. He observed the ship fracture and published what he thought he saw in Philadelphia Bulletin.
Eva Hart	7	Was asleep at the time of the iceberg collision. She was awakened by her father, got dressed, and went to lifeboat station with her parents.	Observed the ship fracture from Lifeboat #14. Saw the stern settle toward the water surface, then upend, and finally sink slowly below the surface of the sea.
Lady Lucille Duff Gordon (Passenger)	48	Heard a long grinding noise with a shock response. "It was not a great crash, but the encounter sounded like a long fingernail rubbing against the ship."	Ship lifted out of the water and this was followed by a tremendous explosion. The stern fell back toward the water surface, while the bow sank beneath the water.
Gertrude Jean Hippach (Passenger)	16	Awakened by the impact of ship and iceberg. Heard a long scrapping noise followed by some bumps; then the interlude was over	None
May Peel Futrelle (Passenger)	35	In the process of going to bed and was hurled from her feet by the iceberg impact.	None
George Brayton (passenger)	-	When collision came was in his cabin about to retire for the night. It was not a severe shock.	Was on Boat Deck and saw Captain Smith when the bow plunged down. After Smith returned aboard, there was an explosion and the ship trembled. Brayton jumped into the water and then heard a series of explosions. Saw the *Titanic* go down bow first.
Daisy E. Minahan (Passenger)	33	At 2130 the air outside became too cold, forcing even the most hardy people inside. Felt a dull shaking and perceptible slow down of the ship.	Heard a terrific explosion which split the ship in two.
Edith Russell (Passenger	-	She was in Cabin A11 when collision occurred. (See text on page)	While in Lifeboat, she heard three separate explosions after the ship sank.
Fireman Frederick Barrett (Crew)	-	Heard sounds like thunder and then saw water poring from a plate seam two feet above floor plate. Quickly exited to Boiler Room #5 where he saw water coming into empty forward starboard coal bunker.	No statement on ship sinking.

Table 4
Tabulation of Survivor Reports

Second Officer Charles Lightoller (Ship officer)	-	Awakened by collision and went to the bridge.	Saw the aft stays of Funnel No. 1 fail and then stack structure fell onto starboard side of bridge. Was thrown into the water, but managed to survive by standing atop overturned Collapsible B. Testified that ship sink intact.
Major Arthur Peuchen (Passenger)			I heard explosions... a sort of rumbling sound ... I imagined the decks had blown with the pressure pulling the ship down...
Steward George Frederick Crowe (Crew)			. and her lights went dim as she broke clean in two...
Fireman Charles Hendrickson (Crew)	-	Awakened by collision and went to his duty station. Noticed flooding in Firemen's Passage.	No statement on ship sinking.

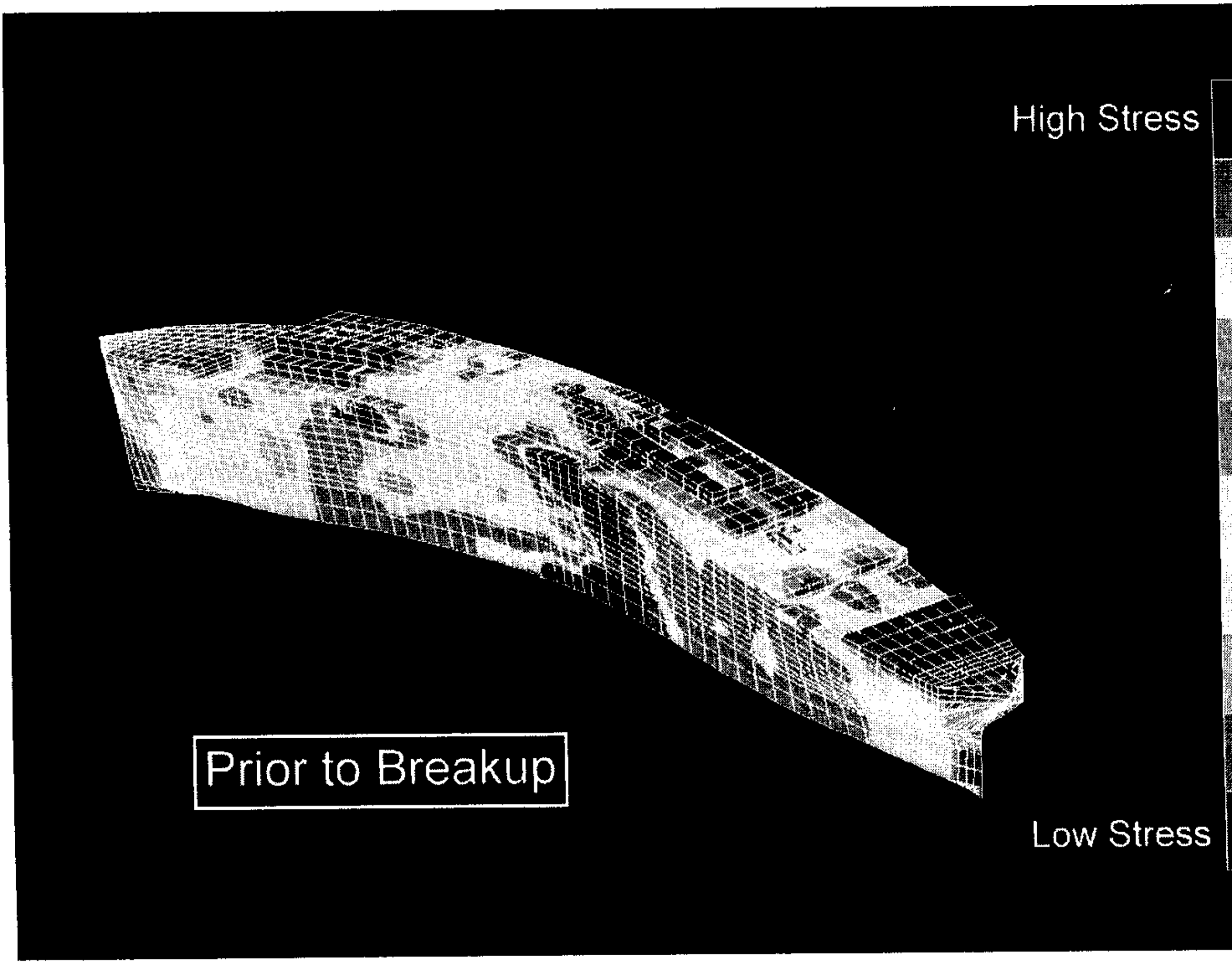

Figure 9

Finite Element Model Results of *Titanic* "Before Breakup".

Matthias of Polaris Imaging may have given us additional clues as to what happened during the ship break up. His discovery of the center portion of the ship, some 57-60 feet in length and lying upside down on the seabed a few hundred feet from the bow wreck, gives any future analyses a better starting point.

Microbiology of the *Titanic* wreck.

With discovery of the wreck in 1985, one of the prominent features was the presence of what appeared to be formations of rust structures on the hull termed "rusticles" by Dr. Robert Ballard. The formations were rust colored and hung down like icicles. The common relationship between rust and the deterioration of iron and steel structures led to the natural linkages between these rusticles and the rate of physical deterioration of the ship. With ten years of observation, there has been ongoing disintegration of the bow wreck featuring the collapse of the top deck over the gymnasium and loss of the canopies to the crow's nest. Much of the bow is covered with these rusticular growths and there are particularly intense clusters growing along the promenade deck, over the stem, and over the port side plates which show signs of buckling.

Before 1996, expeditions to the wreck site did not study the rusticles and their effects on the deterioration of the plates and their rate of growth. The wreck site is clearly oxidizing with many marine organisms (oxygen respiring) living on or around the site.

The color of the rusticles would suggest oxidized forms of iron (i.e. ferric oxides and hydroxides, along with some carbonates) may have caused the rust color. Recent work by Professors Leighly and Long at the University of Missouri-Rolla, using Mössbauer spectro-metry has shown that the rusticles contain goethite (Fe[OOH]). This is an authosiderite which appears to be very pure, fine grained, and contains few defects, which is not surprising considering the low temperatures at which this goethite formed and its possible slow rate of formation. Clearly, since the rusticles contained iron, there is the probability that a very significant fraction would have been extracted from the steel plates of this once great liner to now reside in the growing structures. Questions are naturally raised as to the nature of the events leading to the iron extraction from the hull plates to the rusticles. Is this primarily a chemical, physical or biological event? One of the dives of the submersible *Nautile* in August 1996 focused on this question. Various rusticles were collected and a survey made of the extent of these infestations.

Some basic information was gleaned from the samples brought back to the surface and from subsequent growth from fragments of hull plates and artifacts recovered from the debris field. Analysis was made at the University of Regina, while Dr. Henrietta Mann accomplished electron micrography and microbial identification at St. Mary's University in Nova Scotia, Canada. Based on these studies, it was determined that:

- rusticle's density varies from 1.2 to 1.8,
- they have a retained water content, when drained, of between 25 to 60 per cent,
- the rusticle structure is extremely porous and has an internal surface area of 25 to 95 m^2/g dry weight,
- a rusticle commonly has an iron content of 20-30 percent by dried weight.

Microscopic examination revealed that rusticles are porous, with complex fibrous (or thread-like) structures incorporating various iron dense commonly plate-like structures. The whole rusticle is bounded by a surface rich in iron and slimes with various crystallized structures. Laced through this porous mass are water channels and reservoirs interconnecting with each other and to surface ducts. Major threads interlace these porous structures and some span across the water passageways to give additional mechanical support to the rusticles.

Mr. Scott Miller of the Department of Metallurgical Engineering at the University of Missouri-Rolla examined samples of rusticles using a scanning electron microscope. He performed elemental analysis, as well as semi-quantitative analysis. The result is given in Figure 10. As expected, Iron (Fe) is the dominant element present, followed by Sulfur. The sulfur is present as the sulfate ion, SO_4^{-}, could be from the sulfur in the steel or more likely from the sea water which has 884 part per million content of sulfur [12] The silicon will be shown to be mechanically entrained as silica, SiO_2, from the ever-present sand at the ocean bottom.

Dr. Mark Shumsky of the Materials Research Center at the University of Missouri-Rolla performed x-ray diffraction determinations to identify the compounds in a sample taken from a rusticle and from a massive piece of the corrosion product taken from a piece of steel. The same three compounds were found in these two samples, but in differing concentrations in each sample; silica, which is sand and discussed in the previous paragraph, goethite (FeO(OH)), and iron oxide sulfate, also known

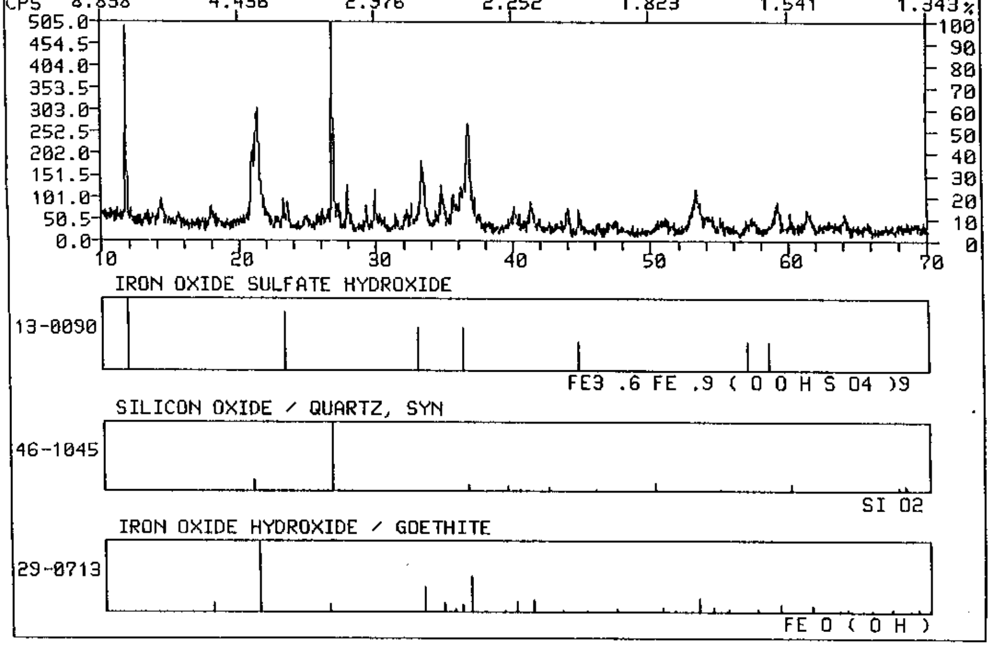

Figure 10

Elemental Analysis and Semi-quantitative Analysis of a Rusticle.

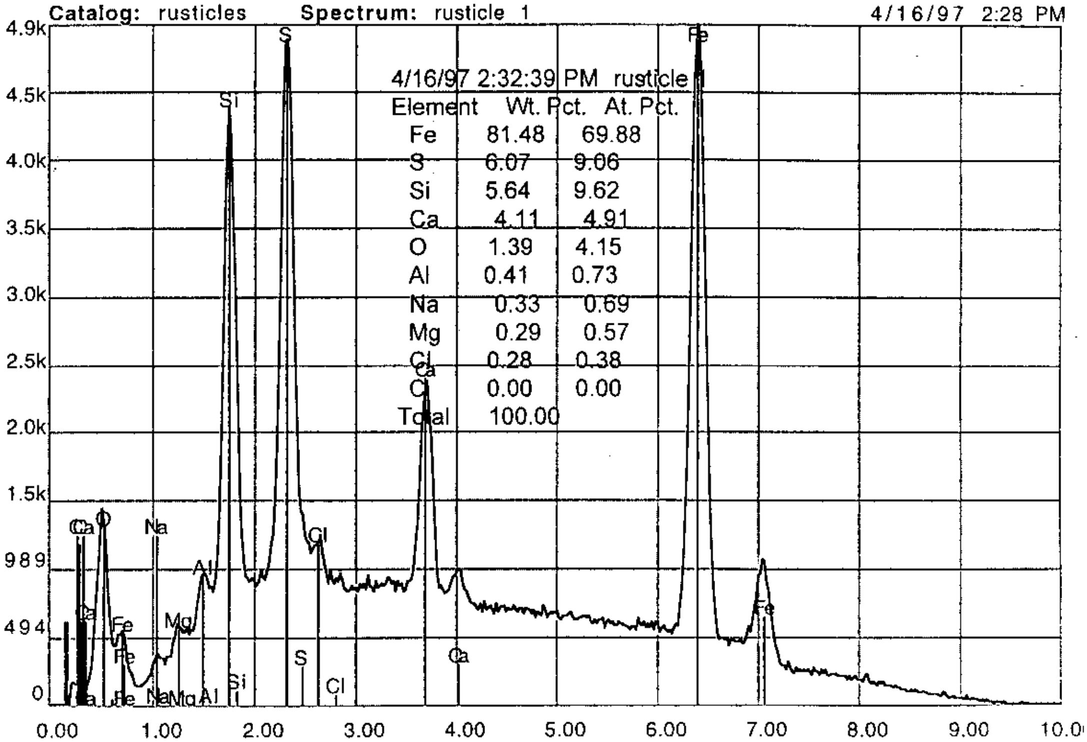

Figure 11

Diffraction Pattern of a Rusticle.

as green rust, ($Fe^{+2}_{3.6}Fe^{+3}_{0.9}(O^-, OH^-, SO_4^{--})_5$)). It is a mixture of ferrous iron, Fe^{+2}, and ferric iron, Fe^{+3}, plus a mixture of anions (O^-, OH^-, SO_4^{--}). In Figure 11, the diffraction pattern is given.

Much remains to be learned from these rusticles in terms of their basic biology and chemistry, but it is equally important to evaluate their likely contribution of the physical compromise of the existing *Titanic* structures. Since the rusticles contain high concentrations of iron which has almost certainly arisen from the bio-extraction of iron from the steel, it is likely that the growth of rusticles will exacerbate the weakening of the steel plates and eventual collapse of the hulk. The rusticles appear to be bio-concretions, that is a hardening porous concreted mass which has formed, at least in part, through a biologically induced colonizing by various microbial growths.

Three principal forms of rusticle growth were detected on the bow wreck of the *Titanic*. The large structures with extensions hanging down the sides of the hull could be clearly seen deflecting the direction of water flow at that site. For example, the starboard hull near the stem is buckled inward. This has caused a change in the flow pattern, resulting in the horizontal bending of the hanging section of the rusticle pointing downstream to the flow. Most of the appendages hung vertically in the relatively slow water current of 1 to 1.5 knots from stem to stern. The second form of rusticle was a concentric clustered type, which remained tightly attached to the hull and showed little sign of growing quickly. The buckled port hull plates close to the stem were heavily festooned with this form of growth. This suggest they may have infested the damaged steel plates. The third type of rusticle has a confluent enveloping form of growth, able to penetrate into gaps and cracks in the steel plating as well as envelope surfaces with a continuous coating of rusticles. These forms often contain embedded coal, glass fragments, clays, and stones that have landed with other debris on the *Titanic* since her sea bed impact in 1912.

The microbiology of the rusticle reveals that bacteria and fungi are present, and tends to be clustered consortial forms of microbial activity sometimes dominated by Iron-Related Bacteria (IRB), Sulfate-Reducing Bacteria (SRB), and fungi. The more centralized passages within the rusticles are often darker brown or black. Tests were conducted to determine the aggressiveness of the growths and the different types of bacteria present. Of particular interest were the SRB groups which produce a positive reaction and concurrently release colloidal floc to the water. This resembled the "sea snow", prevalent around the *Titanic*. Parallel examination of a tuberculous formation on a recovered copper telegraph revealed the presence of sulfur-oxidizing bacteria, *Thiobacillus*, but no SRB, IRB, or fungi.

At the time of the microbiological investigation dive to the wreck, there was a considerable amount of "sea snow". These are flocculent colloidal floating particles that gradually descend like a gentle snowfall. The "sea snow" is white in color and could be seen collecting on any lateral catchment site, such as the shoulders of the rusticles. Although the rusticles are generally shades of orange through brown and purple, the coating of "sea snow" gives them a grey appearance.

The robotic arm on the *Nautile* was used to test the strength of rusticles, 6 feet long and 2-3 inches wide. A gentle touch of the midpoint of the rusticle caused a burst of red dust, outward for some 30 centimeters, from a fixed site (presumably a duct). Clearly the physical pressure of the robotic arm caused some hydraulic pressures within the rusticle structure which were relieved by the venting of liquid through a duct on the opposite side to the point of impact. The emergence of this red dust prompted a second try with a gentle touch. This time the rusticle's arm disintegrated in a diffuse yellow cloud that enveloped the *Nautile* in a cloud for several seconds. At the same instant, the foot of the rusticle detached and floated down in a circular manner into a collection tray on the *Nautile*. It was recovered for further examination and analysis. This exercise, however, revealed that the rusticles are delicate structures with some ability to flex and vent red dust, but which collapse when moderate physical force is applied.

Two types of *in situ* culture platforms were placed on the Bridge Deck of the *Titanic* to determine the presence of bacterial activity. The first type used strips of unexposed but developed Fujichrome 100 A.S.A. film folded in a concertina fashion within a cellulose textile. This was carefully laid flat onto the rusticles so that the bacteria would travel upward through the textile to the film's emulsion. Since the emulsion is black with the primary colors and composed of gelatin, the bacteria were able to degrade this gelatin protein causing the emulsion to erode and reveal some of the colors. The bacteria which etched the gelatin are proteolytic. The textiles on one of the culture platforms that was *in situ* for 20 days became coated with the pigments released from the etching film emulsion, showing that proteolysis had occurred. When this platform was recovered and examined at 40X magnification, complex patterns created by the bacteria mining the gelatin were observed.

The second type of culture platform utilized a modified BART™ (Iron Related Bacteria, IRB and Total Aerobic Bacteria, TAB) which had a perforated conduit connecting the underside of the bio-detector to 10 mm (0.4") above the underlying rusticle. Here, the bacteria penetrated the test vial and essentially removed the crystallized selective medium. The IRB test was in place 20 days before recovery and it appeared that the medium from this test vial had been taken up by the rusticle underneath. These experiments revealed that the rusticles include proteolytic bacteria as well as IRB and aerobic bacteria. More specific identification of these bacteria is on going.

Dissection of a rusticle reveals a somewhat randomized relationship between the various porous, plate-like, and water-bearing structures with threads very commonly found interconnecting these various components. The microbiology of the rusticle reveals that there are both bacteria and fungi present in this growth, but there tends to be clustered consortia of microbial activity sometimes dominated by IRB, SRB, and the fungi. The more central passageways through the rusticle are often a dark brown or black, suggesting more reductive conditions which could be more suitable for the SRB rather than the oxidative conditions that would support the IRB and fungi. Various consortia were detected using the Biological Activity Reaction Tests (BART™). All of the above microbial groups recovered can be described as aggressive from the various tests of the rusticles examined by this technique.

The impact of the rusticles on the *Titanic* remains a critical issue. If they are rich in iron extracted from the ship, there is an inevitable consequence that the ship structure will weaken and eventually collapse. A number of observations can be made concerning the rusticles, based upon the coverage of the exposed hull plates with rusticles. From visual inspections of the bow of the *Titanic*, it is estimated that 65% of the side shell, ranging between 0.75 inches to 1.0 inches, 25% of the bulkhead plates which vary in thickness from 0.375 to 0.625 inches, and 10% of the machinery were coated with attached rusticles to a mean depth of 0.8 inches. A preliminary estimate indicates the mass of rusticles at no less than 650 tons, which could be interpreted to include 178 tons of iron (assuming a 27% iron content). From a visual inspection of the bow section, it is estimated that 65% of the 0.75-inch plate , 25% of the 0.375-inch bulkheads, and 10% of the machinery may now be coated with attached rusticles to a mean depth of 20 mm (0.8 inches). Preliminary calculations indicate that the mass of the rusticles may weigh as much as 650 tons which could include as much as 175 tons of iron. These highly porous and expansive structures on the bow wreck have an internal minimum surface area of almost 6,280 square miles. Since there is no adequate method to complete a more accurate assessment of the rusticle infestation within the hull or the loss of iron from the wreck itself, it remains uncertain how much iron has been extracted from the *Titanic* steel thus far.

At the University of Regina in Saskatchewan, Canada, Dr. Roy Cullimore has just begun analyses of the rusticles. These studies will require a data bank to project with confidence the rate of bio-deterioration of the *Titanic* to the point where the two hulls would no longer exist as definable entity.

Disproving of Myths Surrounding *Titanic*.

Several myths concerning the sinking process of the *Titanic* have been refuted by the work of this recent expedition to her wreck site. First and most importantly, the 90-meter (300-foot) gash theory attributed to the sinking of the *Titanic* is folklore. The iceberg did not penetrate the steel, but instead compromised a main riveted seam deep below the waterline, which resulted in popped rivets, broken caulking, a parted seam, and micro cracks extending into the plate surfaces from the rivet holes. It should also be noted that on the Mohs Scale of Hardness ice is much softer than steel.

There may have been some holes punched by the iceberg, but these occurred near a riveted seam. These holes, however, were mostly in Cargo Holds Nos. 2 and 3, as determined from the sonar imaging. The other compartments also showed damage centered around a riveted seam. It is important to note here that the low impact strength of the steel, grain size, presence of oxides, overabundance of manganese-sulfide inclusions, and the unusually cold water temperature would have aided the propagation of fractures from the rivet holes.

Second, on the basis of evidence in the debris field and the testimony of some of the survivors, the ship started to break up at the surface.

A third discredited myth was the cause of the loud noise heard as the ship upended thought to be displaced boilers, pianos, dishes, and other items crashing through bulkheads, as some writers have suggested. The loud noises emanating from the ship as it lifted out of the water originated from the tearing and mutilation of thousands of square feet of steel. There is a slight chance of a possible steam explosion in the piping in Boiler Room No. 1. When -2 °C seawater came in contact with the hot steam piping under 215 psi (1.48 MPa) of pressure, something catastrophic may have happened. Pieces of steam piping are strewn around the debris suggesting piping failures.

Another disproved myth was that the ship sank because water poured from one subdivision to another. Table 5 summarizes the area of damage along the length of the *Titanic* from a computer analysis made by Mr. C. Hackett and Mr. John Bedford, referred to earlier. The sonar scan of the starboard side of the bow wreck has substantiated these flooding calculations and those made by Edward Wilding back in 1912. The 1996 computer investigation showed slightly different areas of damage, but it was still spread over six compartments with openings that varied as tabulated in Table 5. Although the mean value of the 1996 computer-derived flooding areas are slightly more than Wilding's estimate of twelve square feet provided to the 1912 Mersey Inquiry, in terms of the compartments affected, it does indicate that total area of flooding seems rather small to sink a ship the size of the *Titanic*. The results from the sonar scan also support these estimates. What is important is that the flooding through these openings decreased within the first hour of flooding although the ship plunged deeper by the bow, reaching as much as 400 tons per minute. During the second hour of flooding, the rate of flooding was almost at an equilibrium, but increased once openings in the hull and decks became immersed. Flooding that did occur was not an overflow over the tops of watertight transverse bulkheads from one compartment to another described in many publications, but took place along decks which were not watertight. The downflooding took place through openings for access or piping, cabling, and ventilation cuts. This type of flooding is more consistent with the way the ship actually filled with water after the collision took place. It appears that Cargo Holds Nos. 2 and 3 received the greatest damage with Boiler Rooms Nos. 5 and 6 receiving slightly smaller impacts as the ship began to swing clear of the iceberg. Also, there was some overflow of water from Cargo Holds Nos. 2 and 3, but along the deck structure, into forward compartments during the early stages of flooding.

In reviewing the final stage of the sinking process, there are two possible explanations for the separation of the bow and stern:

- The bow and stern sank separately, with the center section or third piece breaking off during the plunge to the bottom.
- The stern was dragged down by the bow which was still attached to the stern portion by a damaged inner bottom. The third piece would break away during the descent to the bottom.

The authors believe that the second theory is more likely. With the bow portion flooded, there were some 16,000 tons of negative buoyancy tugging at the stern portion after the hull started to split apart. A weakened double bottom section still held the two portions of the hull together. According to eyewitness testimony, the stern slowly dropped towards the ocean surface and then began to rise again. This further weakened the inner bottom at the ends of what was to become the third piece. At some distance below the water surface, perhaps a 100 feet or more, the two sections separated and continued their separate journeys to the seabed below. The third section between Boiler Room 2 and half way through the Reciprocating Engine Room also broke away at this time. This section was the result of a buckling failure in the inner bottom and explains why only half of both reciprocating engines remained in the stern section.

Separating the damage that took place above the water surface from that which occurred below is extremely difficult. To aid in this analysis, Mr. Livingstone and Mr. Garzke have divided the sinking into four stages, assigning a probability of the four stages of the *Titanic*'s sinking as follows:

Iceberg damage - 85%
Ship breaks apart about 100 meters below surface - 50%
100 meters to seabed - 10%
Impact on the seabed - 25%

The difficulties in segregating the damage to the hull arise from the many forces that acted upon the ship during its sinking process and its descent to the ocean floor. Implosion of tanks and tight structures, particularly the refrigerated holds, would weaken hull structure and make it more vulnerable to other forces such as water rushing by as the bow or stern plunged to the bottom. This makes it very difficult to determine the origin of damage to the stern section during its plunge to the bottom. However, the seabed is unusually hard and there is an

Table 5

Summary of Hull Damaged Areas by Compartments

	Compartment	1996 Computer Calculations (From Reference [5])
o	Fore Peak	0.60 Square Feet
o	Cargo Hold No. 1	1.50 Square Feet
o	Cargo Hold No. 2	3.10 Square Feet
o	Cargo Hold No. 3	3.30 Square Feet
o	No. 6 Boiler Room	2.80 Square Feet
o	No. 5 Boiler Room	1.30 Square Feet
	Total Area	12.60 Square Feet

absence of a crater for the bow and stern section as there have been for other shipwrecks. The absence of a crater indicated that the stern section, in particular, slammed down hard on the seabed, possibly without the sweeping type of encounter that we believe that the bow had. This created a significant shock response from the impact. Weakened structure, piping systems, and equipment would have been vulnerable to such a shock response. In particular, equipment made of cast iron would have been particularly vulnerable to such a seabed impact.

The destruction of the stern is certainly the most striking aspect of the *Titanic* wreck and the effects of implosion damage wrought during the sinking process. The aft portion of the stern wreck is more deeply embedded in the sediments than its forward end. The structure around the aft peak tank has remained intact and was also stoutly built. A change in frame spacing to 2 feet was to protect the ship from wash of the propellers and pounding in a seaway during heavy storms. There is some reason to believe that the propeller shafts were bent up so that the propeller blades were brought closer to the underside of the stern. This evidence leads us to believe that the stern end struck the seabed first. The decks in the aft end are curled back like an opened sardine can. The decks in the forward end are pancaked on top of one another over the half remains of the reciprocating engines. Some implosion is involved in the stern wreck and at different times during the plunge. These implosions at different times weakened the structure. In its descent to the bottom, the stern structure was subjected to ripping forces as water streamed by. Both four-story, 400-ton engines were broken in half as the vessel made its plunge to ocean bottom. We believe that their bed plates were fractured as the double bottom buckled and failed, allowing the third section some 60-80 feet to fall independently to the seabed. Parts of a piston rod and crankshaft have also been found in the debris field.

The geology of the area in which the *Titanic* sank may also be a factor in the damage to the stern. The bottom sediments in the area of the stern wreck appear to be a very dense mud or a highly-consolidated sediment. The softer portion may have been eroded away by the strong currents that exist in this area. In fact, during David Livingstone's dive, the *Nautile* was slowed by a very strong current of almost 2 knots. The strength of the current over the years prior to the arrival of the *Titanic* wreck probably had seen the softer sediment eroded away and the exposure of a harder sediment. The absence of a crater around the stern wreck was due to a harder sediment than in the area of the bow and the angle of encounter with the seabed. The shock forces generated upon hitting this seabed were sufficient to cause damage to already weakened structure from implosions during the descent to the bottom. A future expedition to the wreck site needs to explore the geology of the wreck with core samples being taken at select areas.

John Maxtone Graham in his book [13], wrote "...the five boilers in Boiler Room No. 1, farthest aft, were cold, having been put out days before: the Southampton coal strike had prohibited the use of all the boilers." Mr. Maxtone Graham gives no sources for this assertion. These boilers were primarily used in port for hotel services and auxiliaries requiring steam power. The amount of coal distributed around the debris field is testimony to the fact that there was plenty of coal in Boiler Room No. 1 and the adjoining bunkers on the other side of the transverse bulkhead between this boiler room and Boiler Room No. 2. These two spaces were the only boiler rooms which could yield coal in the amount found in the debris field. The coal in other boiler rooms would have stayed with the ship.

There is some credence to the story that the *Titanic* was trying to make a fast run. Bruce Ismay was anxious to have the ship outperform the speed of her sister ship *Olympic*. There was no possibility that either of these ships could win the "Blue Riband" as they had a top speed of 22 knots. By comparison, the *Lusitania* and *Mauretania* were capable of maximum speeds of better than 26 knots. On the *Titanic* during the night of 14-15 April, twenty-four of the twenty-nine boilers were on line at the time of the iceberg collision. A discussion was reportedly held between Ismay and Captain Smith during the morning of April 14. Considering the ice conditions being received from other ships, it would seem plausible that Captain Smith wanted to postpone the maximum power run until his ship was clear of the ice field being reported ahead.

Time Line of the Sinking Process. In creating a time line, one must remember that while experiencing a catastrophe such as this, time may seem compressed. Someone describing a 10-minute interval could in fact be experiencing one hour. The engineering personnel of that period did not have wrist watches, but pocket watches, so to access their watches would be more of an effort than a flick of their wrists. With the bending, squatting, and shoveling of coal, they may not have had their time pieces and any times quoted by them are estimations. The time line in Table 6 has been enhanced by the metallurgical and structural analyses done by Gibbs & Cox, Inc. and the authors.

The last fifteen minutes of the *Titanic* was a nightmarish experience for crew and passenger alike. Scrambling up tilted decks or ladders, it became difficult to hold on as the ship began her final plunge. Once the downward descent started it was, in the words of Chief Baker Charles Joughin, "like riding an elevator down to the water".

What happened below the water surface is difficult to recreate, but a few facts are known. Every effort was made to make the aft compartments of the *Titanic* watertight. As the stern section was pulled further under the water surface, hydrostatic pressures were increasing at the rate of one atmosphere every 10 meters so that compartments could have imploded at different intervals. This was verified by the testimony of Edith Russell who heard three explosions after the stern had disappeared below the water surface. The implosions weakened structure, such as the decks and bulkheads, and with water streaming by during its plunge to the bottom, some structure was ripped away or compression of plates began. In the initial phase of separation, a double bottom piece 57-60 feet long from Boiler Room No. 1 and half of the Reciprocating Engine Room broke away, allowing the bow section to glide to the seabed below while the stern section may have started to tumble. Once the tumbling ceased, the stern end, being the more hydrodynamically efficient portion of the stern, pointed the way down to the seabed below.

The third piece of the ship is believed to have separated from the stern at this time. Upon reaching the ocean floor, the rudder knifed into the sediments and the outboard propeller shafts were forced into the sediment up to the propeller hub. It appears that they were bent upwards by the force of this encounter. Soon afterward the forward end of the stern section came crashing down. The shock forces generated by this impact were sufficient to compress already weakened structure and damage piping systems.

Sonar imaging has located the center or double bottom section from the *Titanic* some 500 meters and 45 degrees from the end of the stern section. This would place this smallest main section of the ship forward and to starboard (which is actually the port side) of the stern section. The "big piece", that was the focus of attention in the 1996 Expedition for retrieval as an artifact for museum display, was located about 600 meters to port of the bow section and at an angle of 135° from the stern end. This scattering of debris within the debris field is yet another indication of the violence in the hull failure.

Over 70 years passed before the wreck was located. During this time, there may have been some corrosion occurring in the stern section that caused further collapse of this structure. Once this happened, the fragile rusticles disintegrated and the process had to be resumed. The present condition of the stern wreck makes it more difficult to separate the damage caused by impact from that of the sinking process. Some evidence for this conclusion is that the colonies of rusticles in the bow are far more advanced than those in the stern.

Final Thoughts. It is a pity that Thomas Andrews was allowed to perish with the ship. Captain Smith should have ordered him into a lifeboat so that the technical reasons of the *Titanic*'s loss could have been better assessed. His testimony at the hearings into the causes of the disaster could have been more revealing and it probably would not have taken 84 years to finally figure

Table 6
Reconstructed Time Line of Ship's Sinking

1140, April 14	The *Titanic* strikes an iceberg and damages plating in six of her forward watertight compartments.
0000, April 14	A total of 7,450 tons of water gains entrance to the *Titanic*. The bow begins its plunge into the ocean.
0010, April 15	Captain Smith and Naval Architect Thomas Andrews complete their tour of the damaged compartments. Andrews warns the Captain that the ship has no more than two hours to live and he should begin an immediate evacuation of passengers.
0025, April 15	Order passed to load the lifeboats and at 0045 Lifeboat 7 with a capacity of 65 is lowered to with only 28 occupants.
0045, April 15	The first distress rockets are fired.
0050, April 15	The forward coal bunker bulkhead in Boiler Room No. 5 fails, flooding that space completely.
0125, April 15	Panic overcomes those still left aboard with only a few lifeboats left and over 1,700 people still remaining on board.
0130, April 15	The wireless is running on emergency battery power. This is acknowledged in reports of weakened radio signals received from ships in the area. Flooding of Boiler Room No. 4 is well advanced, but there is no flooding report yet aft of this space. Almost 31,000 tons of water have now gained entrance to the hull.
0150, April 15	Water begins to spill into Boiler Room No. 4 from Boiler room No. 5 and openings in decks above.
0205, April 15	The forward expansion joint is pulled open, snapping the aft stays to the forward funnel. It falls on the starboard side of the bridge, crushing structure and people in its path. The stern is high out of the water exposing the propellers and rudder. Captain Smith releases radio operators Bride and Phillips from their duties.
0210, April 15	Boiler Room No. 4 is completely flooded and the bow begins to slip below the water surface. The amount of water is now over 39,000 tons! Water reaches the bridge front and begins to rise towards the Boat Deck where the collapsible life boats are in the final stages of being rigged for a few of the 1,500 people who still remain aboard. The stern starts to slowly rise. The crew of Boiler Room No. 2 abandons this space as flooding there commences.
0215, April 15	The crew of Boiler Room No. 1 are still at their posts, but the tilt of the deck makes it difficult to walk. The watertight door to the Reciprocating Engine Room is closed and the bilge pumping ceases.
0217, April 15	The ship has reached such a trim angle that it is difficult to walk. Normal activity in the engineering spaces is no longer possible. Many of the crew struggle up the escape ladders in an attempt to reach the open deck. The officers remain at their posts. The dynamos continue to run unattended and on residual steam.
0218, April 15	The bow trim has been increasing at an alarming rate, but a sudden lurch downward in the bow trim threatens to spill the fires from the furnaces. Steam still flows from the boilers as liquid flashes from falling pressure. Soon thereafter, the bottom structure fails and there is a random chaotic fracturing of the upper hull plating and superstructure. Flooding of Boiler Room No. 1 has begun. At this point the steam lines to the dynamos and the cabling under the upper deck structure snap plunging the ship into darkness. Eva Hart in Lifeboat Number 15 sees the stern slowly falling towards the water surface; she is hoping the stern will float to save her Dad.
0219, April 15	The stern begins to rise again as the bow begins its plunge to the ocean bottom and begins to drag the stern down with it.
0220, April 15	The stern disappears below the water surface, taking with it 1,522 people. Only 705 stunned survivors are left in twenty lifeboats scattered around the sinking site.

out what happened. Although Bruce Ismay was soundly criticized for actions in saving himself, we are fortunate, however, that he survived the disaster. He did provide some technical insights that led up to the disaster; otherwise there would have been a huge void of technical information.

The breakup of the *Titanic* was a violent end to a beautiful ship of her time. Although the ship was very well designed to resist flooding, the longitudinal extent of the damage outmatched her subdivision. The massive flooding caused stresses in her hull girder that were not envisioned in her design. It appears that brittle fracture did occur, but the steel itself was not a major factor in the collision with the iceberg. However, the steel metallurgy did quicken her end. The bending forces involved at the moment Boiler Room No. 4 flooded were so massive that the best of modern steels would have been powerless to resist them.

The steel of the *Titanic* shows significant yield strength when compared to present day mild steels. However, the bulkhead and hull plate show a coarser grain structure than would be permitted by present standards of classification societies. The steel was semi-killed and not fully killed as required by those societies. The level of oxygen, phosphorous, and sulfur in the steel is beyond the prescribed limits of standards now in effect for minor elements in steel. Although the sulfur does cause embrittlement, it was a minor factor in the damage that brought about the initial flooding of the *Titanic*. The presence of too much sulfur increases the ductile-brittle transition temperature. However, it was a major factor in the structural failure that occurred in her final moments above the water surface. The flooding itself caused such large stresses to occur that it induced the hull fracturing which was enhanced by the steel metallurgy. Even so, rules for the construction of merchant ships still do not require steels tobe notch tough at temperatures down to the freezing point. The authors urge that classification societies need to take urgent action to require low-temperature ductile steel for ships that will ply icy waters.

There is one other very important point concerning the steel chosen for the *Titanic* and her sisters. Harland and Wolff purchased the very best steel that was available for the construction of these and other ships it built during that era. Although the steel's metallurgy does not match today's standards, this reflects the progress that has been made in the past 100 years in the manufacture and rolling of steel at the mill and the regulation of the minor elements in steel as a result of Liberty ship and T2 tanker failures during World War II. Not only has shipbuilding progressed significantly in terms of material procurement and methods of construction, but so has steel metallurgy.

With all the limitations in the steel's metallurgy, the use of wrought iron rivets, and the punching of the rivet holes, the iceberg encounter was made fatal with the involvement of a riveted seam. It appears from the sonar imagery that cracks propagated along the riveted seams and the wrought iron rivets failed in the freezing temperature allowing water to stream in whenever the ship and ice mass met. We agree with Bedford and Hackett that the fatal damage is restricted to a total area of 12.6 square feet.

There has been much speculation that if more lifeboats had been provided, there might have been more people saved. From evidence at hand, it appears that the rule of women and children first only was applied without exception on the port side and to a lesser degree to the starboard lifeboats. With the order to swing out the lifeboats at 0020, five boats with approximately 180 people were launched from the starboard side and three boats with 120 people from the port side. If we ignore the two collapsible lifeboats that floated off the ship, a total of nine boats were launched in 55 minutes on the starboard side and a similar amount in 70 minutes to port. It is fair to assume that the restriction of the boats to women and children did cause some time delays in launching the lifeboats, but also resulted in some 17% more people being put into the starboard boats in lesser time. It is clear that the launching of the boats was not rushed, possibly to avoid panic, possibly due to the unfamiliarity of the crew to the lifeboats and their launching, and the fact that many thought the ship would not sink so fast. This led to some 450 unfilled seats. If there had been no order for women and children first, a greater proportion of first and second class male passengers would have been saved. Since 161 women and children went down with the ship, an additional 300 seats were available for men. This leaves over 1,000 passengers and crew to be accounted for.

If the ship had been equipped with two tiers of lifeboats as shipbuilder and davit vendor had designed the ship, the lifeboat capacity would have been about 2,200, almost equal to the number of souls on board. Another alternative was the provision of larger lifeboats. However, some of the officers were reluctant to fill the lifeboats that the *Titanic* was carrying for fear that the maximum number of occupants (65) would cause failure of the craft as they were being lowered to the water. Harland and Wolff had tested the strength of the lifeboats by lowering them with 65 men aboard. There were not failures.

If we now assume that when Captain Smith was told by Mr. Andrews that his ship would sink in two hours, can we assess if the lifeboats could have been filled and lowered more quickly? Since 9 boats were lowered in 55 minutes, we can apply this rate to the 36 boats (including four collapsibles) aboard in our theoretical model. This would have taken 100 minutes assuming the 20-25 minutes of boat preparation that actually did occur. Thus even in ideal circumstances, there would not have been sufficient time to evacuate all the 2,222 people on board, even with 36 lifeboats. Part of this was due to passengers' and crew's belief that the ship was unsinkable and the newness of the crew to the ship. Also there were no lifeboat drills during the voyage or on Sunday, April 14th even though the latter had been a White Star Line tradition. Another difficulty was rousing passengers without creating a general alarm. Serious evacuation began only one hour after the collision. When the ship's stern began to emerge from the water, rigging the lifeboats to davits, or even accessing them would have been difficult. Added to this would be the time involved to retrieve the lifeboat falls and to re-attach these to the lower tier of boats.

The 1996 *Titanic* Expedition demonstrated the usefulness of the deep-diving submersible, manned or unmanned, to explore deep-ocean wrecks. With the improvements in the side-scan and sub-bottom sonars, these wrecks can be outlined for study before a manned dive in a submersible is made to pinpoint important aspects to be studied. Although photographic study of a wreck is a useful piece of scientific analysis, other procedures need to supplement it. Crucial evidence needs to be taken from the wreck site or the vessel itself for further study. Finite element analysis can be used in determining the stress levels and possible areas of failures based on the evidence retrieved at the wreck site. In the case of the *Titanic*, the steel was a crucial element to determine why the vessel fractured at the surface. The finite element model demonstrated that stress levels exceeded the yield strength of the steel, leading to its break up into three pieces. Sonar imaging proved very useful in creating images through the sediments on the starboard side. These images helped to determine what damage occurred from the iceberg-ship collision that was hidden from human eyes. These techniques were used in the exploration and analysis in the loss of the SS *Derbyshire*, for example. The knowledge gained from an analysis of her loss will influence the design and operation of bulk carriers for years to come.

Acknowledgements. The authors would like to thank Mr. George Tulloch, the salvor of the *Titanic* and president of RMS TITANIC, INC., for allowing this expedition to conduct the analyses described in this report as well as providing some of the photos of the ship in the paper. A photographic encounter with the *Titanic* wreck could not produce the knowledge gained from the metallurgical analysis of the steel from the debris field, the sub-bottom scan of the bow wreck and the side-scan sonar inspection of the debris field, or the biological studies of the rusticles that now are growing on the steel surfaces of the ship. After 85 years, it is now possible to know what may have really happened on the night of April 14-15, 1912.

The authors wish to thank D. Brown of the Laclede Steel Company for the chemical analysis of the *Titanic* steel samples, Messrs C. Ramsey and S. Miller for their work in the electron micrograph, Messrs. J. Jones, G. Papen, M. Roberson, and D. Murphy of the School of Mines and Metallurgy shop at the University of Missouri- Rolla for their assistance in preparation of the test specimens, and student assistants Katie Felkins and R. Tayloe for their help in performing the impact and tensile tests.

We also wish to acknowledge the assistance of Dr. Richard Johnson and Dr. Harold Reemsnyder for their invaluable assistance in reviewing this manuscript and the help of the latter in confirming the metallurgical test results done by Professor Leighly and his staff as well as conducting tests on the steel from the tender *Nomadic*. We also want to thank Ed McCutcheon, formerly with the Ships Structures Committee for his advice and suggestions on the brittle fracture of C1 cargo ships, T2 tankers, and Liberty Ships during World War II.

The authors wish to thank Peter K. Hsu for his assistance in sketching Conditions B-6 and B-7 from Reference [5]. We would also like to thank Marion Todero and Michelle Fry for their assistance in the editing and formating of this paper.

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APPENDIX A

Time Line Analysis of Stoker Frederick Barrett's Testimony

Around 1130, lookouts Reginald Lee and Frederick Fleet spotted a heavy haze directly ahead. At 1136, the dark outline of a large iceberg is now in view some 500 yards off the starboard bow. Fleet rings bell three times and notifies bridge by telephone. At 1137, First Officer William Murdoch pulls the engine telegraph to STOP position and orders a port turn to avoid hitting iceberg.

Circa 1137 Engineer Shephard in Boiler Room No. 6 hears a bell ring and spots the red signal for the STOP command from the engine telegraph and orders dampers to the furnaces of the boilers be closed. Crew in Boiler Room No. 6 shouted "shut the dampers".

1140 The *Titanic* begins her encounter with the iceberg and Stoker Frederick Barrett hears a crashing sound. He turns around and observes water coming into the ship through a large tear in the hull (sic - parted seam) about two feet above the floor plate and approximately two feet from where he was standing. A bell is ringing to signal the closing of the watertight door to Boiler Room No. 5. Barrett and engineer James Hesketh jump into Boiler Room No. 5 through an opening for the watertight door as it begins to descend. Barrett looks into the coal bunker in the forward corner of Boiler Room 5 and notices that the tear he saw in Number 6 Boiler Room extended two feet beyond the main transverse bulkhead into Boiler Room No. 5.

1200 Barrett returns to Boiler Room No. 6 via escape ladder as he receives an order from Engineer Hesketh for "every man to his station". He notices that there is eight feet of water above the floor plates in Boiler Room No. 5 (this means there was 14 feet of water above the tank top).

1201 Barrett and Hesketh return to Boiler Room No. 5 using the escape ladders.

1205 Once back on the floor plate level in Boiler Room 5, Hesketh and Barrett meet Engineers Harvey and Wilson who are tending to the bilge pump in boiler Room No. 5. Barrett notices the space is still dry and that flooding in the coal bunker on the forward starboard side of that Boiler Room was like water from a fire hose.

1207 Barrett receives orders from Engineer Harvey, who had been on the telephone, for Barrett to remain in Boiler Room No. 5 while all other stokers were sent up to the deck above. Engineers Harvey, Wilson, and Shephard remain with Barrett. No flooding noted in Boiler Room No. 5 at this time by Barrett.

1210 The lights in No. 5 Boiler Room went out as the circuits were being switched to the emergency dynamos topside on Saloon Deck.

1215-1220 Barrett goes to passage over fire room to retrieve flashlights and notes upon return that lights in Boiler Room No. 5 were back on again.

1223 Barrett looks at water gauges for the boilers in Boiler Room No. 5 and finds the glass tubes empty. There is no water in the boilers in this space as steam had been vented from boilers.

1225 Engineer Harvey requests Barrett to get 15-20 men to help him (Barrett) to keep the fires down in the 30 furnaces there.

1240 All fires are extinguished in furnaces and 15 men return to deck above for assignment. Much steam is created by pouring water on the coal fires.

1241 Engineer Harvey requests a manhole cover to a pump be removed, leaving opening in the deck. Engineer Shephard in an effort to do something falls into hole and breaks his leg. The steam from water poured on the fires in the boilers obstructs his view.

1256 Barrett attends to Shephard and his broken leg. At 1256, the non-tight coal bunker bulkhead in the forward starboard corner of Boiler Room No. 5 fails and water surges into this boiler room. Efforts to save Shephard fail and Barrett quickly ascends an escape ladder. Barrett is adamant that the water did not come from above but through the bulkhead and a pass between the boilers.